Small Scale Innovation for Large Scale Progress: A Clean Tech Rural Development Model Using Quality of Life Indicators to Select Optimal Renewable Energy Solutions

Small Scale Innovation for Large Scale Progress: A Clean Tech Rural Development Model

Using Quality of Life Indicators to Select Optimal Renewable Energy Solutions

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Abstract

The energy poverty challenge sits in an estimated $6.4 trillion clean technology market opportunity in developing and emerging markets over the next decade (World Bank, 2014). As a result, private sector investments have magnetized towards renewable energy technology solutions that while innovative, are limited in scalability. However, large-scale electrification has seen narrow success, often only using income levels as a proxy for development – a myopic measure for Quality of Life (QOL) in rural areas with drastically different livelihoods than their urban counterparts.

Thus, my critical research objective was to determine which Rural Energy Development Solution(s) (REDS) best catalyze QOL improvements in rural communities to increase return from international development dollars and private sector investment. My primary hypothesis was that small-scale solar REDS (i.e., solar lamps and Solar Home Systems (SHS)) have the highest degree of correlation with QOL indicators, suggesting a sustainable and significant development opportunity for rural communities in Malaysia. However, the model showed the impossibility of predicting REDS fit without taking both a holistic and customized assessment of each village's situation. In Kampung Dew, an islanded microgrid has the most promise, largely given the anticipated growth in energy need from the village's budding ecotourism business and accountable management entity expected from the stable local government. In contrast, a SHS is an optimal match for Kenyah due to its community-oriented longhouse living arrangements; ongoing displacement as a result of hydrodam construction make the ability to pump water to irrigate its farmlands even more important.

Methodology for this research centered on determining Clean Tech Rural Development Model (CTRDM) variables to build a robust and applicable cost-benefit model. First, by assessing environmental, economic, and social implications, I identified the pertinent costs and benefits of a representative range of three REDS from the smallest to largest application (i.e. solar lamp, small-scale solar home systems (SHS), and mid-scale microgrid electrification). This investigation uncovered a net positive impact from each REDS after accounting for up-front capital, implementation, and maintenance costs. Both per household and government perspectives were crafted to provide a balanced viewpoint of each REDS.

Second, I identified relevant QOL inputs and created assessment mechanisms for each of these variables, quantitative where possible, and qualitative where not. This composite of inputs provides a comprehensive assessment of Environmental, Economic, Social, and Governance factors (e.g. number of households, proximity to grid, access to biofuel) that tailor REDS selection to a specific rural locale.

Lastly, customizing this model for two villages in Peninsular and Sarawak Malaysia determined which solutions yielded the highest impact on QOL indicators relevant to rural development, i.e. income level, health, education, and gender inequity.

CTRDM can thus serve as a decision tool that forecasts the extent to which REDS impact QOL indicators for a specific region and guides government policies and private investment in REDS implementation. While rural villages in Peninsular and Sarawak, Malaysia were used as test cases for the CTRDM, the customizable inputs make the model applicable to a wide range of countries considering rural development through clean technology solutions. As REDS advance, further studies, using the replicable methodology, can be conducted to build out the cost-benefit model.

Acknowledgements

Research can mimic life, in that if you devote time to it, persevere through the sometimes unexpected challenges, and share with your loved ones, it will offer you a rich and rewarding experience. Such has been my encounter with this thesis, which would not have been possible without several critical mentors.

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Chapter I

Introduction

In the 21st Century, development has arguably been spurred by innovative technology – software that has sped us into the information era, wearable inventions that facilitate human productivity, and machinery that allows us to better harness natural renewable sources of energy to power progress. Despite all of these discoveries, half the world's population remains in energy poverty with no cessation of increased global energy demand. In other words, three billion people have irregular access to or no source of electricity in their daily lives, as population growth and the demand for natural non-renewable resources grows. At a micro level, 20% of the global population or 1.3 billion people lack household access to electricity and clean cooking facilities 80% of whom inhabit rural areas (OECD/IEA 2012).

Research Significance and Objectives

While large scale infrastructure projects that connect rural areas to the grid offer a means to bring these communities out of the dark, electrification has generally failed to tackle long-standing issues of poverty; furthermore, funding and multi-organizational support for large-scale electrification programs have declined over the last three decades as "recent country-specific studies of Blunck (2007) and Kürschner et al., (2009) have revealed not all of the anticipated impacts actually unfolded," including improved air quality, decreased mortality rates, heightened access to education, and social equity (Brossman, 2013).

On the other end of the spectrum, privately funded applications of clean technology have fueled social progress in quicker, albeit confined ways – facilitating mobile payment capability for a small business or allowing a household to stay active past sunset. Thus, large potential can be found in small scale solar technologies that spur critical "step change" progress. This bottom up approach is especially relevant to countries that have seen rapid growth amidst rural villages, where energy access could overhaul the way of life without the necessary transmission and distribution infrastructure electrification requires. Understanding how to unlock the power of small scale solar technology to improve quality of life could revolutionize how we approach sustainable development of rural/urban dichotomized countries that shrinks the income gap.

With these considerations in mind, my research revolves around the following objectives:

- Determining the extent to which small scale solar technologies (vs. large scale electrification) are effective as a sustainable development solution tackling energy poverty in rural areas
- Developing a model that guides which solutions (small vs. large scale) are most effective in closing the widening energy inequity in a rural/urban divided economy
- Using Malaysia as a test case for this model and understand its applicability to craft an optimal international development tool for other countries

Influencing the direction of private capital investment and/or global funding in the technologies that can yield the largest amount of international sustainable development.

Background

The intersection of clean technology and rural development creates an ecosystem of largely untapped opportunity to improve quality of life for communities most impacted by energy poverty.

Energy is at the Nexus of Critical Issues within the Sphere of Sustainable Development

With energy at the crux of many of our global issues today, innovative ways of harnessing, using, and saving this resource can unlock progress in myriad forms, from climate change mitigation, to economic advancement and educational opportunities, to healthcare access. The inextricable linkage between energy and development is illustrated at a macro-level when comparing global indices. A cross-country comparison shows the correlation between the Energy Development Index and the Human Development Index in 2010 (Figure 1).

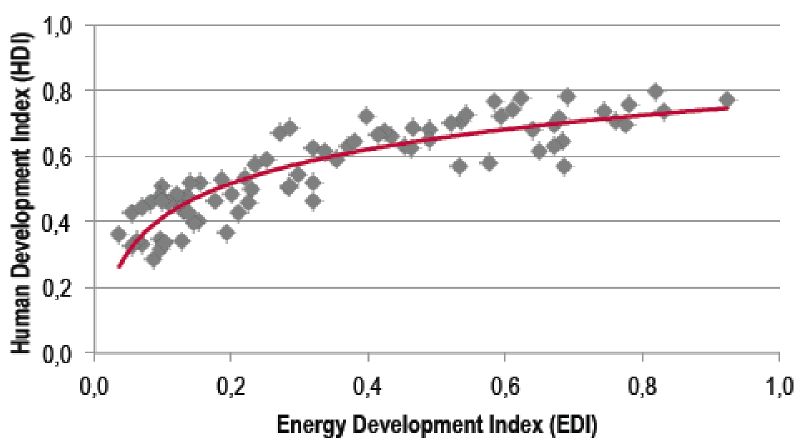

Figure 1. Global cross-country comparison between EDI and HDI, 2010.

In comparing these indices, the International Energy Agency (IEA), accounts for "indicators at the household level and the community level as well as considering not only access to electricity but also to clean cooking facilities" (Brossman, 2013). Since "the informational base of [EDI] is broader than the one underlying the usually stated electrification rates (OECD/IEA 2012: 541-542)," we have a more comprehensive understanding of what dimensions of poverty can be affected by increased access to energy (Brossman, 2013).

Despite this connection between energy and development, creating sustainability solutions continues to be a challenge. While everyone has a stake in solving our energy crisis, this goal is marred by many vested interests – those of governing institutions, local utilities, private sector companies, and community stakeholders – that have slowed down the realization of environmental, economic and social progress.

Climate Change Disproportionately Affects Poorer, Rural Communities

Sustainable development is a daunting challenge in the face of global population growth and ever increasing energy demand, putting heightened pressure on limited natural resources and the Earth's overall carrying capacity. The World Bank studied this connection between environmental factors and their effect on several dimensions of poverty, uncovering how poor communities are disproportionately affected by climate change:

- Opportunity declines when poor people who depend on natural resources for their livelihoods can no longer do so because of environmental resource degradation and lack of reasonable alternatives.
- Capacity is impaired when poor people's health is damaged by dirty water, dirty air, or diseases related to the environment (such as malaria). Environment-related illnesses are some of the most deadly killers and causes of sickness amongst the poor.
- Security is threatened by natural disasters and climatic variation. As we have argued, the poor tend to be more physically vulnerable to natural disasters and have fewer resources to enable them to ride out the shocks (World Bank, 2000).

Since climate change hits poorer communities harder, it follows that environmental progress can beneficially impact health, economic livelihoods, and security of rural communities in a long-term fashion. In fact, "renewable energy resources appear to be one of the most efficient and effective solutions" for sustainable development (Dincer, 1999).

The Answer? Clean Technology.

In 2007, Ron Pernick and Clint Wilder published "The Clean Tech Revolution: The Next Big Growth and Investment Opportunity" that for the first time laid out a strong business case for commercializing clean technologies from a financial perspective. They painted the picture of a highly profitable and increasingly mainstream clean tech business around the world and noted the global trends of resource shortages, climate change, and security threats as an impetus for these innovative technologies to spur the next round of economic growth.

While their analysis was highly financially driven, subsequent research has pushed the bounds of impact beyond mere monetary benefits. In 2014, the World Bank published a seminal study that analyzed the promise for green industries in these so-called developing countries and their capacity to be competitive relative to the existing established economies of the developed world. This report builds on the premise that "making climate-smart investments can have, overall, a positive economic impact, particularly among the largest greenhouse-gas-emitting economies in the developed world" (The World Bank, 2014); it takes this "climate-smart development" model and applies it to developing countries where significant positive benefits can be reaped by technology investments that limit emissions, while simultaneously lasting "investing in technologies to restrain emissions and by developing new clean technology industries that can build resilience and limit further climate damage" (The World Bank, 2014).

High Potential for Clean Technology to Spur Financial and Economic Development

In terms of quantified opportunity, "the expected investment across a wide range of clean technology sectors, just in the world's developing and emerging economies, will exceed $6.4 trillion over the next decade" (The World Bank, 2014). This forecast however, is not solely dependent on large industry – “about $1.6 trillion of that total offers an opening for small and medium-sized enterprises (SMEs) –key drivers of future job creation” (The World Bank, 2014). The financial case for clean technology starts to go beyond mere environmental and financial benefits in creating a basis for employment, workforce development, and long-term innovation with the investment in clean technologies. Latin America and Africa are among the largest markets for SMEs in clean technology with potential market sizes of $349 billion and $235 billion respectively.

Senior Director Anabel Gonzalez of the World Bank Group Trade and Competitiveness Global Practice puts into perspective this major growth potential that home-grown clean-tech industries can have in developing countries: “[they] can create a sustainable and wealth-producing sector of the economy while simultaneously addressing such urgent development priorities as access to clean and affordable energy, clean water and climate-resilient agriculture.” It is this extension into social impact – a cross-over into meaningful aspects of quality of life like employment, food security, and resource efficiency that can be unlocked via energy – that is at the crux of this research to understand the power of clean technology beyond climate change mitigation.

Nevertheless, these market-sizing analyses largely ignore the social impact attached to the forecasted injection of investment and economic activity from implementation of energy solutions. To fully comprehend the extent to which clean technology development can go past environmental benefits and in what form it will come, energy poverty and its many social ramifications must be understood. Only then can the impact of clean technology in addressing these quality of life indicators be assessed to determine whether the progress from implementation is adequate to lift entire communities out of poverty.

Energy Poverty Solutions that Create Social Progress Must Involve Renewables

Increasing access to energy is only beneficial if the energy generated is from renewable and clean sources. Granted, coal mining, fracking, and oil production can create strong economic viability for a country, but from an impartial net impact perspective, closing the energy access gap with fossil fuels only exacerbates the very problems developing countries face, e.g. negative health impacts from pollution, climate change harboring spreadable diseases like malaria. Without integrating renewable energy in the sustainable development equation, the crux of the issue around energy access is simply postponed. While "energy from traditional sources will help alleviate some immediate concerns from energy poverty, [it] will create potentially more disastrous impacts for the world's most vulnerable populations down the road and continue to leave the world in clean energy poverty" (Relich, 2011).

Currently, solar is the most scalable form of clean technology and thus, has the largest potential to take advantage of the linkage between environmentally sound solutions and progress on multiple poverty fronts. However, the range in scale of solar technologies has yet to be evaluated in terms of their relative effectiveness for sustainable development. This thesis research will address the question of which level of scale – from single units to grid connection – are most effective. Foundational to this assessment is an understanding of existing Rural Energy Development Solution(s) (REDS) and their comparative effectiveness in Brazil, China, Bangladesh, and Kenya. Couldn't see that you defined in Introduction, but good to remind

Large-Scale Rural Electrification: Weak Development Connection

The challenge of rural development has historically been met with support for utility grid extension – an approach dominant in developmental economics from the 1950s to 1970s when electrification was seen as the main catalyst for progress. A plethora of studies have focused on geographic regions in South and East Asia, as well as Latin America, to review the impact of rural electrification (Barnes, 1988; Bose, 1993; Chaurey, Ranganathan, & Mohanty, 2004; ESMAP, 2003; Gerger & Gullberg, 1997; Munasinghe, 1988). None of these studies analyzed alternative options, such as decentralized electricity infrastructure or small-scale technologies. In addition, many of these reviews focused on poverty levels as an indication of impact, rather than extending the measures to multiple dimensions of quality of life or contextualizing improved income levels within the rural lifestyle. This overall body of research concludes that as a development tool, rural electrification is limited in its ability to affect "the poorest" classes and that the cost of electricity can be cost-prohibitive to these communities, as Table 1 below suggests (Pearce, 1987).

Table 1. Studies of rural electrification impact and findings around the world.

Rural electrification in developing countries

Table 1. RE and the rural poor.

Author	Countries surveyed	Conclusion
Nathan[a]	Bolivia, Colombia, Costa Rica, Ecuador, Guatemala, Nicaragua, Philippines	RE benefits the poor 'but not the poorest'
Tendler[b]	Costa Rica, Colombia, El Salvador, Philippines	Household users are 'the better off among the rural population'
McCawley[c]	Indonesia	Electricity is a 'luxury'
AID[d]	Bangladesh	Households with electricity better off than average
Bijort[e]	Kenya	Ditto
Plunkett[f]	Pakistan	Ditto
Kessler *et al*[g]	Ecuador	Residential users almost entirely in income groups below national average
Butler *et al*[h]	Bolivia	
Goddard *et al*[i]	Costa Rica	Half the homes with electricity were below the (official) poverty level
Mandel *et al*[j]	Philippines	40% Filipino rural poor 'are not able to afford power'
Cecelski and Glatt[k]	Various	Small % of household that are connected have 'relatively higher incomes' than unelectrified households
Samanta and Sundaram[l]	India	Residential connections varied from 18% to 100% (West Bengal, Punjab respectively)

The flaw in the case for large-scale rural electrification (RE) is based in assumptions that ancillary infrastructure will be built to leverage the new power source provided to the community. Starting in the 1980s, this theory on rural electrification as a prerequisite for development was reassessed in favor of evidence that "rural electrification was a necessary but not sufficient condition to trigger rural development" (Barnes, 1988; Foley, 1992; Munasinghe, 1987; Pearce & Webb, 1987). Significant local factors that constrained electrification were largely overlooked, e.g. density of rural population as a ratio to existing land, low purchasing power, and limited potential for load growth:

> Long distances and difficult geographic terrain meant greater electricity losses and prohibitive operational, maintenance, and administrative costs. Moreover, for many industries, proximity to main markets (primarily in urban areas) was more decisive because transport costs, not electricity, were a bigger share of production cost (Lury, 1976) (Kirubi, 2008).

These demand-side constraints, along with a World Bank commissioned costs and benefits evaluation study, succinctly captured the shift in thinking on the impact of rural electrification. As evidence from developing countries demonstrated, "RE has not, by itself, triggered industrial growth or regional development" for lagging low-income rural economies as persistently claimed by the development community (World Bank, 1995 p. 2). The study found that where other prerequisites of sustained development were absent, demand for electricity for productive uses did not grow. RE is economically justified only when the emerging uses of electricity are strong enough to ensure sufficient growth in demand to produce a reasonable economic rate of return on the investment. Thus, for myriad reasons of financial, economic, and infrastructure concerns, RE is not necessarily the most suitable sustainable development REDS.

Case 1: Rural electrification in Brazil. More recently, the impacts of rural electrification outside of income levels have been analyzed; in a study of Brazil's rural electrification program Luz Para Todos (Light for All), the health implications of decreasing the transmission of schistosomiasis from electricity-enabled water pumping was examined in rural Minas Gerais State. From 2001 to 2009, 142 households were interviewed to qualitatively understand their domestic water use habits and how they changed with access to powered water facilities that could pump water from wells and storage tanks. A quantitative analysis looking at the multiple regression of changes in the number of households receiving electricity, types of water supply, water contact and *S. mansoni* (snail vectors for schistosomiasis) infection showed a decrease in schistosomiasis prevalence in the study area of Virgem das Gracas. Nevertheless, overall results were inconclusive, as the infectivity of well water and schistosomiasis transmission did not show statistically significant results (Kloos et al., 2012).

Thus, while the provision of electricity has been shown to be an important and necessary component for rural development, the solution is inadequate on its own. Its limitations are nested in its inability to reach all communities, overcome cost-prohibitive factors of electricity consumption, and spur long-term infrastructure facilities that could leverage access to reliable power sources. These projects include building roads and transportation systems, but also extend to growing business and social infrastructure like schools, health facilities, and markets. Recognizing these inherent limitations from decades of research across global case studies behooves us to examine alternative solutions for the rural development challenge. A bottom-up approach using small-scale solar technologies could address the limitations of its large-scale alternative.

Small-scale Solar Technologies: Impactful with Limited Reach

The economies of scale that have resulted from the advancement of solar photovoltaic (PV) technology has brought decreased manufacturing costs and allowed for wider application of the renewable energy tool. From solar powered transportation in the air and on the road, to solar desalination and solar cookers, the innovation around this space continues to engender new solutions.

Case 2: Small-scale solar lamp success stories. The impact of small-scale solar technologies is powerful, albeit limited in its scalability. Despite the fact that solar lamps and lanterns fail to provide a power source for additional appliances, they have seen wide adoption for a number of reasons. For example, solar lighting tools are a relatively simple technology to design and manufacture, making it an attractive endeavor for private sector mission-driven companies to enter the market, e.g. Barefoot Power, Little Sun. The global development community has also incorporated these small-scale solar technologies into their programs for their simplicity, ease of implementation, and relatively low educational requirements (e.g. brief demonstrations at a local store are sufficient to illustrate usage and benefits). Upfront capital costs are comparatively low, and where prohibitive, can be made viable through micro-finance.

As a result, for the benefits to the environment (reduction in use of fuelwood), health (as an alternative to burning kerosene lamps), safety (minimized fire hazard), and education (improved literacy rates), solar lamps have seen broad acceptance as development tools with no shortage of success stories where they have been sold, implemented, and used. In the Bushenyi district of Uganda, Barefoot Power's Firefly™ lighting products enabled Claire Kenganzi the ability to grow her hair salon business and provide power for her son to study past sundown; Gloria Ingabire of Mbarara Uganda is an Area Health Officer who has spread the use of solar lamps to capture savings, but also improve health awareness around the risks of burning paraffin and kerosene (Barefoot Power, 2014).

Nevertheless, case studies analyzing the long-term impact of solar lamps are remiss in the literature review of small-scale solar appliances and their intersection with rural development, suggesting that by themselves, small-scale solar lamps are limited in the breadth of impact achieved. Investigating this hypothesis further, the connection between solar lamp implementation and literacy rates appears to be most significant to the QOL discussion, as educational attainment creates a pathway out of poverty. However, through multiple regression analysis, a case study in Assam, India, pinpointed the three explanatory variables responsible for literacy rate trends for people above 6 years of age: household electrification rate, road density per 1000 km^2 and sex ratio (Kanagawa, 2008). Solar lamps alone did not drive the marked improvement in education, although a plethora of success stories tout the educational benefits.

Thus, the costs and benefits associated with small-scale solar appliances are complex. Considering them in the larger context of supporting external factors like a community's economic livelihood, commitment of private funders, mechanisms of government support, and availability of alternative REDS will help clarify how best they can be leveraged to drive sustainable development.

Case 3: Solar Home Systems in Bangladesh. Building on the widely accepted concept that access to modern energy has a positive impact on different dimensions of poverty, a deep look at the implementation of household solar systems in Bangladesh uncovers the myriad ways in which a small-scale approach can be effective in spurring development.

Solar Home Systems (SHS) and Small Solar Home Systems (SSHS) are decentralized PV systems that are designed for off-grid households with low energy demand, i.e. typical nominal power output "ranges from 30 – 130 Watt peak (Wp) (Komatsu/Kaneko/Ghosh 2011: 4022)," (Brossman, 2013). Electricity generated from this system is stored in a lead-acid battery that can then power lighting fixtures and small electrical appliances, e.g. mobile phone chargers, radios, or black and white televisions.

A body of research exists that investigated causal linkages on the micro-level between decentralized photovoltaic systems and positive social outcomes; other publications focused on PV technology and productive use (Blunck 2008), the economic viability of solar systems (Chakrabarty/Islam 2011; Mondal 2010), or non-income factors behind the decision to purchase a (S)SHS (Komatsu et al., 2011; Brossman, 2013). So while the idea of assessing the impact of small-scale Solar Home Systems is far from new, the Bangladeshi case study pulled out two novel elements: first, given its recent publication, it was able to run a methodologically sound comparison between different levels of scale, i.e. SHS versus SSHS, as the dissemination of the latter began in 2008; second, it treated the nuance of gender-sensitivity as recommended "by the GIZ Gender Strategy (GIZ 2012: 10) and Gender in Reporting Guidelines (GTZ 2010: 3-6)" by "explicitly targeting both male and female household members as interviewees, using gender-disaggregated questionnaire forms, and addressing gender-related aspects directly in all appraisal techniques" (Brossman, 2013).

The results of this Bangladesh case study showed that these small-scale solar systems had significant impact at the residential household level. Figure 2 lays out the multiple dimensions on which (S)SHS implementation had a positive outcome, from economic, human, socio-cultural, and political capabilities to gender gap and environmental benefits. This research also uncovered the inter-related nature of these dimensions by which to measure quality of life. Gender was the most notably affected facet, as it cut across all poverty dimensions.

While powerful considering the range of capabilities (S)SHS was found to have in this community, the system is not without limitations. For example, (S)SHS were not shown to

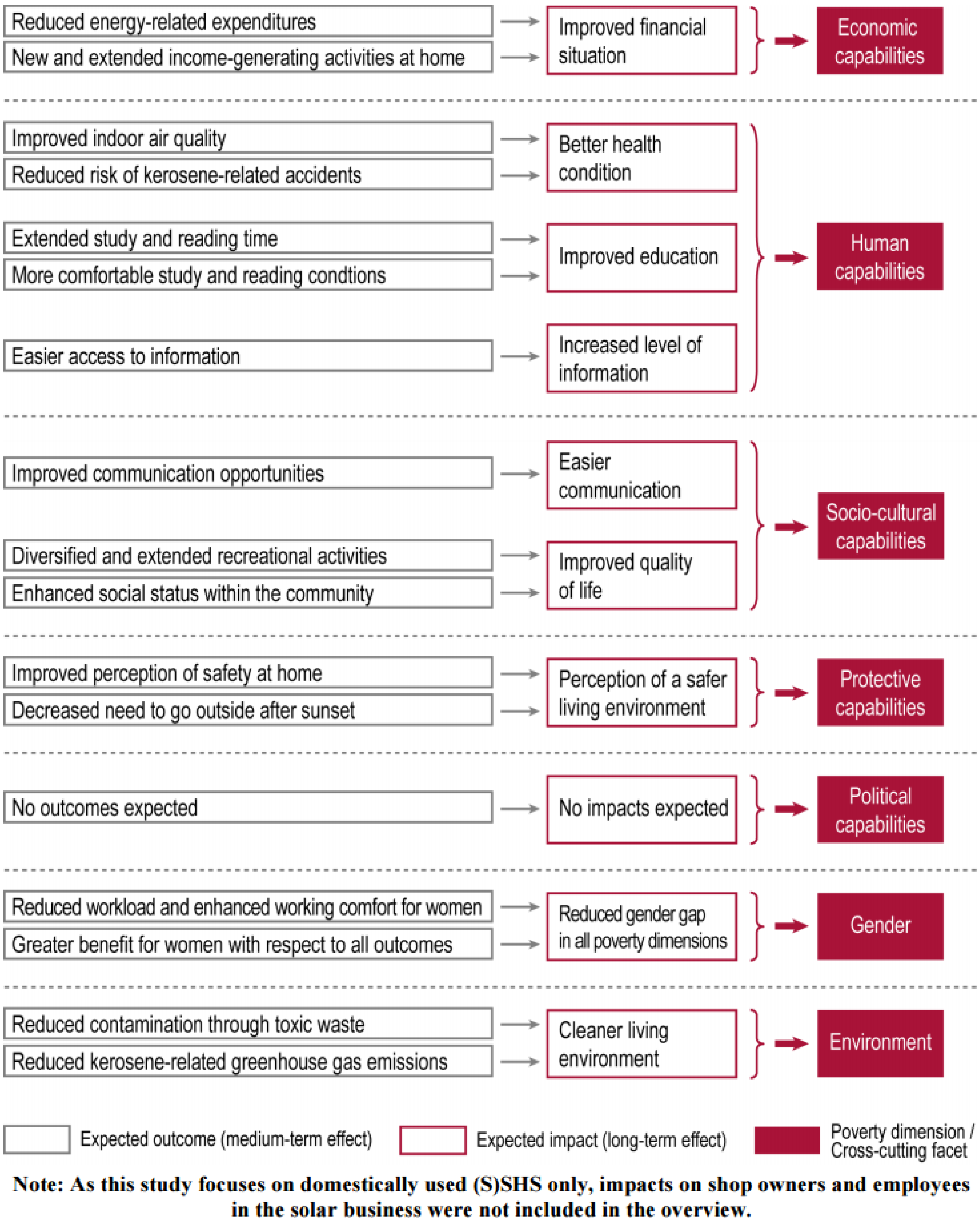

Figure 2. Expected outcomes and impacts of (S)SHS dissemination.

"increase the economic capabilities of their users in the medium term and detrimental environmental effects due to inappropriate battery recycling are likely to occur in the near future" (Brossman, 2013). Unsustainable progress on these economic fronts is not useful for step change development, begging an analysis of how these impacts vary over time. In addition, harmful toxicity risks derived from mishandling of lead acid batteries must be internalized into the environmental cost of this solution. Lastly, no comparison with alternatives, e.g. (S)SHS of bigger wattage capacity, large-scale electrification is conducted.

Mid-scale Microgrids: An Alternative Model

Case 4: Microgrid in Kenya. Having now seen the limitations of both small and large-scale efforts to power a rural locale, a community-based electric microgrid case study in Kenya offers a look at the viability of a mid-scale REDS. This research solidifies the connection between rural electrification and rural development on three fronts:

> 1) Access to electricity enables the use of electric equipment and tools by small and microenterprises, resulting in significant improvement in productivity per worker (100–200% depending on the task at hand) and in a corresponding growth in income levels in the order of 20–70%, depending on the product made;
> 2) Access to electricity simultaneously enables and improves the delivery of social and business services from a wide range of village-level infrastructure (e.g., schools, markets, and water pumps) while improving the productivity of agricultural activities;
> 3) Increased productivity and growth in revenues within the context of better delivery of social and business support services contribute to achieving higher social and economic benefits for rural communities (Kirubi et al., 2008).

Overall, the study corroborates that energy access is crucial to development. Using a microgrid allows for a level of scalability across a village that individual solar cookers or SHS cannot achieve. Additionally, the research tested the feasibility of cost-recovery – a recurring limitation of large-scale rural electrification historically. Findings indicate that when local electricity users and/or generators are provided with the "ability to charge and enforce cost-reflective tariffs and when electricity consumption is closely linked to productive uses that generate incomes, cost recovery is feasible" (Kirubi et al., 2008). Thus, the diversity of power sources and rightly sized production capacity of a microgrid reduces greenhouse gas emissions and lowers the often prohibitively high electricity costs that make it unaffordable to villagers under large-scale electrification.

While these results point towards microgrids as the best solution for rural areas to improve productivity, increase income levels and heighten levels of business and social services, the research rests on a crucial assumption-- that complementary infrastructure is available. Just as large-scale electrification is limited by the facilities that can leverage access to power, the success of microgrids is tied to the presence of "markets, roads, and communications…to contribute to increased productivity" (Kirubi et al., 2008). Thus, for rural communities whose economies are based in small and micro-enterprises (SMES) and agriculture, microgrids in conjunction with this complementary infrastructure can spur sustainable development. The domain of inference for microgrid application, however, cannot go beyond villages that do not follow this social construct. Moreover, negative environmental impacts associated with improper use and disposal of lead batteries tied to microgrid systems further behooves a holistic cost-benefit analysis of this REDS. Associated educational programs and community engagement strategies can ameliorate these effects, but add to the financial cost of implementation.

Rural Malaysia: a CTRDM Case Study

Malaysia presents an informative case study on the impact of both electrification and renewables on sustainable development, as the country has piloted both strategies to spur growth. The country's current and prospective outlook for solar power is strong, due to its equatorial location and continuous supply of sunlight. High levels of average annual solar radiation are available across the country, equating to 400 – 600 MJ/m^2 of average solar radiation per month, supporting the push for large scale solar power installations (Figure 3) (Mekhilef et al., 2011).

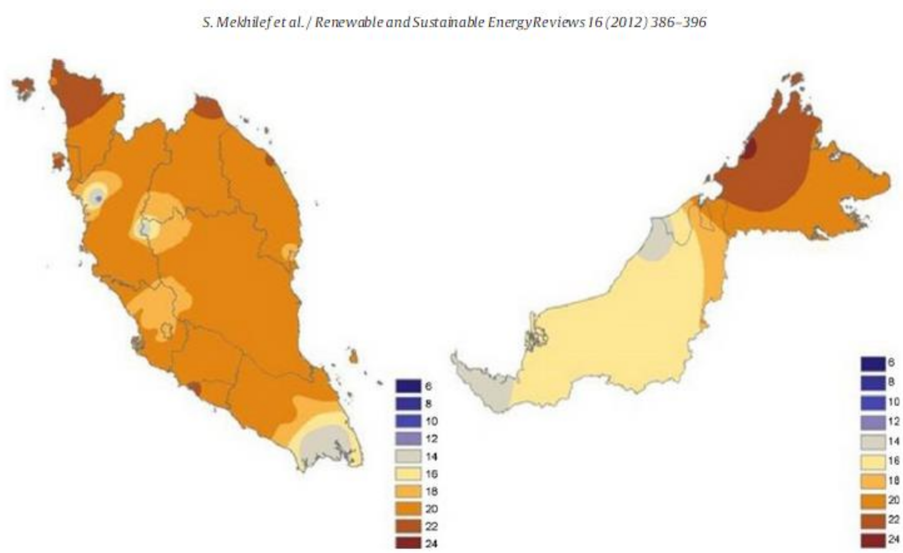

Figure 3. Annual average solar radiation in Malaysia (MJ/m2/day).

In conjunction with a desire to diversify the country's energy sources and the attractive low maintenance cost of solar PV, it was deemed "the best choice for future energy power generation" (Mekhilef et al., 2011). In addition, a number of programs have been established to leverage this potential, namely the Malaysian Building Integrated Photovoltaic (MBIPV) project announced on July 25th, 2005. This program focused on proving the value of solar energy and energy efficiency for the country through demonstration projects that catalyze the local building industry. The 9th Malaysia Plan specifically targeted improving electricity supply in rural areas, resulting in 59,960 housing units being connected to the grid in Sabah and Sarawak. The percentage of rural electrification coverage has increased over a decade of implementation (Table 2).

Table 2. Rural electrification coverage by region, 2000 – 2010 (%).

Region	2000[b]	2005	2010
Peninsular Malaysia	97.5	98.6	98.8
Sabah	67.1	72.8	80.6
Sarawak	66.9	80.8	89.6
Malaysia	89.5	92.9	95.1

Source: Economic Planning Unit and Ministry of Rural and Regional Development.
[a] This refers to rural housing units served as a percentage of total rural housing units.
[b] This refers to Census 2000 data excluding housing units served with private individual generators.

As the majority of rural areas have been electrified, the "crucial challenge facing the power sector in Malaysia currently is the issue of sustainability that is to ensure the security and reliability of energy supply…to ensure smooth implementation of development projects to spur economic growth in Malaysia while diversification of energy resources is critical to ensure that the country is not dependent only on a single source of energy (Leo-Moggie, 1996). At the same time, these challenges must be met without having adverse effect on the environment to ensure sustainability" (Mohamed, 2005).

These issues lend themselves to understanding whether small scale solar technologies can provide more reliability of clean power to rural communities as an alternative to large scale electrification. Thus, while it is apparent that large scale electrification has had a direct impact on development, as evident from the progress Malaysia has made and the favorable energy policies put in place, the studies conducted to date have several shortcomings. First, it is unclear in what ways rural electrification has spurred development, for example, Millennium Development Goals such as a country's income, education, health, Information and Communication Technology (ICT), Bridging Digital Divide (BDD), environmental and security systems. Solar hybrid systems are also used in school-net projects to provide PC and internet connections. Second, it is uncertain whether rural electrification closed the poverty gap in a sustainable way. Lastly, large scale electrification has not been compared with small-scale solar technologies on any dimension.

"In Malaysia, more efforts in Research and Development (R&D) on solar energy are required in order to overcome the barriers to enhance the PV market in the country. One of the major barriers for solar energy is the economic barrier where the capital investment required is very high" (Mekhilef et al., 2011). Thus, the high potential for solar has been untapped due to the cost-preventative capital intensive investment. Understanding the ways in which electrification can support development, the extent to which this development is sustainable and lasting progress, and its comparison to small-scale alternatives, will help overcome this barrier and guide investment to the solutions with highest impact.

Cost-Benefit Analysis

Overall, there is large potential, but no proven method to leveraging small and large-scale clean technologies that close the poverty gap. In the absence of cost-benefit analysis that has been employed to compare these solutions, development agencies and private funding can be misguided in determining the best fitted REDS for a rural area.

The literature review and presented case studies provide a holistic perspective on the ways in which energy and development are inextricably linked. Small-scale technologies are limited in scalability and present some environmental complications, while a body of work on the inability of rural electrification to achieve anticipated results, particularly in the economic dimension, has amassed over the last five years (Kooijmanvan Dijk, 2012). In addition, “critical literature reviews on the relationship of energy and income point out that while at a global level evidence for definite correlations is strong, analyses at a national or regional level have yielded contradictory results” (Brossman, 2013).

Moreover, recent research has also found that a cost-benefit analysis has to be applied to better understand the ramifications of different energy technologies: “reforms should be aimed at catering the energy to the poor to produce any significant impacts on poverty reduction. Future studies of reforms can also focus on the welfare analysis of reforms using cost-benefit analysis, which remains largely limited in the context of developing countries” (Jamasb et al., 2014).

Financing: Major Initial Hurdle

Financing and creating incentives for energy development solutions is a major initial hurdle for implementing clean technologies. Organizations with the technical capability and financial means to fund top down large scale infrastructure development and electrification lack the incentives to do so. With high risk and limited return on these projects, the challenges in connecting rural communities to the grid deter those capable from pursuing rural projects. At the same time, due to recent technology advancements, small-scale off-grid energy projects have become a feasible alternative so long as widespread implementation can be achieved (Relich, 2011). Nevertheless, the return for small-scale projects, as seen in rural sub-Saharan Africa, fails to attract funding from big players more interested in developing large scale renewable energy projects for developed areas that can easily connect to the new and clean generation source.

Thus, top down approaches lack incentives and bottom up solutions fail to achieve scale through widespread user acquisition. Even when both solution types are funded, developed, and implemented, the question of extent of impact remains. With this original research, a solid case for guiding foreign investment and venture capital to the solutions with the highest potential for long-term developmental impact can be built.

Research Hypotheses and Specific Aims

Building off of the substantial body of research that has explored the ability of solar solutions to spur sustainable development, this thesis research will tackle the following original points of investigation:

1. Solutions comparison by scale: Small scale solar technology, mid-scale microgrids, and electrification have been evaluated as individual solutions, but not compared in a holistic net impact sense against each other to determine which is "best in class" on environmental, economic, and social dimensions for a specific locale.
2. Long-term impact: Clean technology solutions have been connected to rural development programs, but not investigated from a long-term standpoint to account for waste management and inevitable growth in demand for energy. Assessing quantitative and qualitative variables from both the government and user standpoint will help craft a full picture of expected impact.

3. Applicability across countries with implications for private investment: No tool focused on rural quality of life has been created to select clean energy solutions that will spur long-term sustainable development and influence private investment. Previous models have been aimed at shaping policy and facilitating decision making at a national level. Building a tool that takes country-specific inputs to project quality of life benefits associated with each REDS will focus private dollars to where they can yield the most impact.

I hypothesize that the application of small-scale solar technologies is superior to large-scale electrification in improving the quality of rural life in economies as it addresses multi-dimensional poverty indicators, narrowing income and gender disparity and improving access to health and education, in countries with rural/urban dichotomies.

Chapter II

Methods

This research employs various methods to build the CTRDM, namely: establishing a mechanism to measure REDS impact on Quality of Life, conducting a cost/benefit analysis of REDS, and selecting representative variables that allow for model customization based on the rural locale of interest.

Correlation between Quality of Life and REDS

Renewable energy solutions hold incredible potential to drive rural development at a far greater scale relative to the impact they create in developed countries. At the same time, income levels are insufficient to measure the extent to which REDS can drive multi-faceted progress in education access, health levels, and living standards. In addition, relating REDS to different QOL indicators helps guide an optimal selection of REDS that is more closely aligned with the coveted lifestyles of rural communities that often would rather preserve their way of life instead of urbanizing.

Multidimensional Poverty Indicators (MPI) of Development in Rural Areas

Using data from the USAID Demographic and Health Surveys (DHS), UNICEF Multiple Indicator Cluster Surveys (MICS), WHO World Health Surveys and special national household surveys, the MPI lays out three main dimensions that starkly illustrate how poverty comprises more than simply an income or GDP assessment. Rather, the MPI extends to fields like

Education, Health, and Living Standard with indicators in each that define the level of deprivation. Given that “this methodology requires determining the unit of analysis (i.e. household), identifying the set of indicators in which they are simultaneously deprived and summarizing their poverty profile in a weighted deprivation score,” it is informative for this research in that it quantifies an extended definition of poverty per household – a central unit around which the quality of life potential through REDS implementation can be understood (Alkire, Conconi, Seth, 2014). Thus, education, health, and living standard are fitting categories to measure poverty alleviation through energy access.

To understand the extent to which these categories offer step change development, the Multidimensional Poverty Indicators (MPI) represented in Table 3 can be further extended through an analysis of how energy access is related to each dimension of poverty.

Energy empowers educational achievement. For example, a 2012 study of village access to energy services notes that “kerosene lamps are insufficient for the purpose of reading (Nieuwenhout, de Rijt et al., 1998), typically producing between 1 to 6 lux (Mills, 2003) (one lux is equal to one lumen per square meter). This light output is well below the recommended lighting requirements for task-specific activities (50 lux (Nieuwenhout, de Rijt et al., 1998)) and reading (200 to 500 lux (Lindsey, 1997; Siemens, 2006)” (Bailey et al., 2012). Solar-powered Light Emitting Diode (LED) lamps offer an alternative to extend studying outside of daylight hours. These lamps are not only more energy efficient, but also deliver “positive impacts on health, the environment, and education” as renewable energy micro-generation technology (Zahnd and Kimber, 2009). REDS can thus replace fuel sources like charcoal, wood, and even kerosene, which are inferior light providers, more expensive per unit of light output than electric-based alternatives, and exacerbate

Table 3. Energy poverty relevance to Multidimensional Poverty Indicators.

Dimensions of Poverty	**Indicator**	**Deprived if…**	**Energy Poverty Relevance**
Education	Years of Schooling	No household member has completed at least one year of schooling.	Electricity facilitates studying outside of daylight hours
	Child School Attendance	No children are attending school up to the age at which they should finish class 6.	Labor needed at home as fossil and/or biofuel procurement is time and resource intensive; other factors like transportation infrastructure at play
Health	Child Mortality	2 or more children have died in the household.	Heating, cooling, and hygiene impacted by accessibility to energy
	Nutrition	Severe undernourishment of any adult (BMI <17kg/m^2) or any child (-3standard deviations from the median).	Motorized tools could scale the production of food sources; other factors like crop sources at play
Living Standard	Electricity	The household has no electricity (no change).	Fundamental need for electricity sources and infrastructure
	Improved Sanitation	There is no sanitation facility (open defecation).	Electricity powers sewage and waste water treatment; larger infrastructure needed
	Improved Drinking Water	The household does not have access to safe drinking water, or safe water is more than a 45-minute walk (round trip).	Electricity usage for water pumps and conveyance; larger infrastructure needed
	Flooring	The household has a dirt, sand, or dung floor (no change).	Not inextricably tied to energy sources
	Cooking Fuel	The household cooks with dung or wood (coal/lignite/charcoal are now non-deprived).	Electric or gas-fired stoves improve air quality
	Assets Ownership	The household has no assets (radio, mobile phone, refrigerator, etc.) and no car.	Varying levels of electricity provision and facilitate asset ownership

(Source: Multidimensional Poverty Index Data Bank and author elaboration, 2013).

MPI conditions specifically regarding educational attainment (Bailey et al., 2012).

Health is inextricably tied to energy access. While the focus on lighting is important to understand the potential to further education, there are fundamental health improvements that are possible with REDS, as the dimension of health is also directly impacted by energy access. "The release of toxins during combustion, contribution to upper respiratory disease, and safety concerns such as fire hazards and accidental ingestion" can be avoided through REDS that would replace fossil fuel heating and cooking mechanisms (Bailey et al., 2012). The chilling fact is that with over 3 billion villagers burning accessible fuels like charcoal as a prime energy source, half of this population – 1.5 billion people – die as a result of the high particulate air pollution emitted in poorly ventilated spaces (Reinhardt, 2006).

Living standards are a function of energy access. Lastly, living standard measured at a household level is another critical indicator of how energy can impact quality of life. Household energy has been defined as a basic human need, as it is central to the satisfaction of fundamental health and nutrition requirements (UNDP, UNDESA et al., 2000). 95% of staple foods require cooking prior to consumption in diets of the developing world (DFID, 2002). In addition to cooking and heating, household energy also powers activities like pumping for irrigation, water and sanitation systems, thus being a critical prerequisite for essential infrastructure (Bailey et al., 2012). Asset ownership of items like a radio, mobile phone, television, refrigerator, and washing machine are also predicated on household energy, and tied to improved living standards and income generation ability.

Indicators of Improved QOL in Rural Areas

For these three categories, there are both leading and lagging indicators to understand how energy can improve quality of life. Leading indicators are defined by energy usage requirements, as both access and sufficient capacity to power REDS is needed to attain a certain outcome, like reading at night or charging a mobile phone. Lagging indicators provide a sense of how energy access is impacting the MPI categories, as shown in Figure 3; Education is measured by years in school, while Health can be indicated by child mortality rates with a range of key indicators available to measure Living Standard. These lagging indicators will be useful to determine the extent to which REDS implementation as guided by the CTRDM is furthering a community's development.

Table 4. Typical energy service requirements in the form of electricity for off-grid populations in developing countries.

Development Need		**Typical energy services for off-grid households**	**Electricity Demand kWh /month, per household**
House-hold energy need	Lighting	5 hours / day at 20W for a household	2-6
	Radio/Music	5 hours per day at 5W per household	
	Communication	2 hours per day at 10W per household	
	Potable water	Electric pump providing the community with 5 litres per day per capita	
Medical services		2.5 kWh / day for basic services in a rural clinic for 100 households	0.5-1
Education		2.5 kWh /day for lighting, water pumping, copying, computer, copier, TV, Video, radio etc. in a school for 100 households	0.5-1
Productive (income generating uses)		5 kWh / day for equipment used by workers from 10 households	0-20
TOTAL			3-30

(Source: Malaysian Commonwealth Studies Centre MCSC, 2012).

Leading indicators are informed by development needs associated with kilowatt hours of energy required per household to achieve a basic quality of life standard powered by electricity (Table 4). These development needs addressed by energy provision align with those of the MPI, from Living Standards associated with household energy usage, to medical services that support

Health, and energy enabled activities to further Education. In sum, 3 – 30 kWh per month per household is expected to fuel a village's development needs. At this level, REDS can power progress in the areas of Education, Health, and Living Standard that represent multiple dimensions of poverty.

Cost/Benefit Variables and Assessment Mechanisms for each REDS

Understanding the net impact of REDS implementation is crucial to make an informed decision about which renewable energy solution aligns best for a specific community's QOL and development goals. For example, while microgrids promise power reliability and the highest level of energy access across a village, the investment required to design, develop, build, and maintain the system may be too cost prohibitive to provide worthwhile return. Thus, selecting a representative range of the scale that REDS can have, and then assessing a comprehensive view of the environmental, economic, and social costs and associated benefits expected from implementation of each, is a necessary basis from which to build the CTRDM.

Selection of Renewable Energy Development Solutions

With this understanding of how REDS have potential to improve QOL, an analysis of the extent to which each REDS can further these MPIs can further guide the selection of an optimal clean technology solution to power progress. This research necessitates an identification of the costs and benefits associated with each REDS, so that its implementation can be considered holistically.

The International Energy Association has projected that 55% of additional connections needed to provide electricity to the 1.2 billion people who do not currently have electricity access will depend on microgrids, individual home lighting systems, and other alternatives to central grid connections (2012). So while other technologies powered by fossil fuels can help improve QOL, this analysis focuses on REDS rather than non-renewable solutions. REDS technologies can scale more easily without infrastructure-heavy requirements, demand less capital, offer more environmentally sustainable options, and generally possess simpler supply chains. Furthermore, the cost of many of these clean technologies like solar and LEDs have experienced significant decreases over the last several decades (EASAC EU, 2013).

The next filter applied to the selection of REDS uses the "energy ladder" as a guide, which maps out the range of energy services demand directly related to increases in income. With heightened country development, comes increased energy consumption – however, per capita income increases do not necessitate higher GHG emissions when a community transitions towards cleaner energy sources, thereby avoiding increased pressure on finite fossil fuels. Granted, nontechnical challenges like limited capital, access to responsible management parties, and unsustainable supply chains must still be overcome to successfully transition up this energy ladder (EASAC EU, 2013). With the acquisition of more dispensable income, the demand for assets increases accordingly, from necessities like heating, cooking, and lighting, to more ancillary services like transportation and water conveyance, to finally, supplementary accessories for cooling, and small enterprise. Each REDS was selected to address the general level of energy service demand from individual to household and village application (Figure 4).

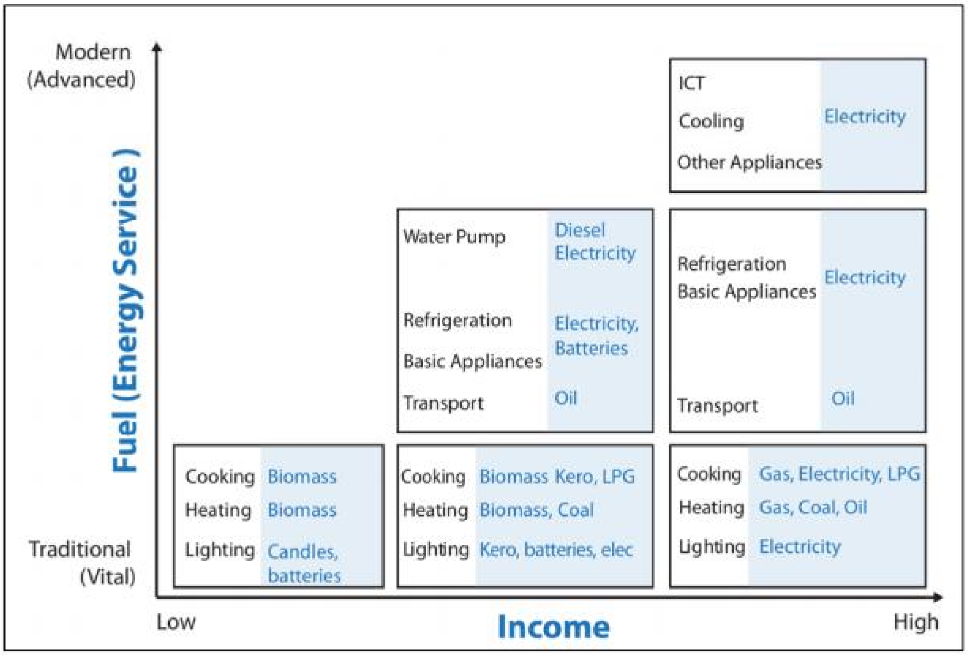

Figure 4. Example of household fuel transition and energy ladder (Source: IEA, 2002).

To provide clarity on these solutions, each REDS is defined below along with an analysis of rural development potential as powered through village level energy, relative commercialization status, and an acknowledgement of potential issues with implementation.

Solar lamp is an attractive small scale REDs. Photovoltaic cells convert solar radiation from the sun's light into direct current electricity. This technology harnesses the planet's most plentiful renewable energy source to convert the sun's energy into electricity that powers a rechargeable and efficient LED lamp. While seemingly simple, a light source can have significant impact on rural development. From the correlation to MPIs, lighting can impact Education with studies past sunset, Healthcare limiting fire and air pollutant risk, and Living Standards by minimizing time dedicated to acquiring fuel for light or facilitating work hours to extend into the night. The United Nations deemed 2015 the International Year of Light, which has spurred focus on this potential and private sector funding to develop solar lamp solutions aimed at developing countries. As John Dudley, the chair of the steering committee of the International Year of Light stated, “an important aim of [the year] will be to promote the use of portable, solar-powered, high-brightness LED lanterns in regions where there is no energy infrastructure. We are hoping that corporates will rally international businesses to drive the costs of solar lights down and to partner with governments to solve the problem of poor lighting” (Dudley, 2015).

As a result, solar lamp commercialization has been driven both from large enterprises like Panasonic evidenced by its 100 Thousand Solar Lanterns Project, and new burgeoning start-ups like Greenlight Planet, and d.light solar committed to transform the lives of at least 100 million people by 2020. D.light serves over 40 countries, through over 6,000 retail outlets, 10 field offices, and four regional hubs” (d.light, 2016). As the simplest REDS, its successful implementation is relatively simple, requiring well-designed pricing of its products to make them affordable and accessible to its target users. Proliferation of this technology has enabled a wide range of activities critical to the livelihoods of villagers. In Uttar Pradesh, solar lanterns illuminate the paths in a brick kiln after nightfall, while in Odisha where less than half of the Indian state’s 42 million people are connected to the grid, villagers can continue to trap fish at night because of solar lamps; in Uganda, mechanics credit solar lanterns with enabling them to work longer hours and earn more money at their motorcycle repair shop (Figures 5, 6 and 7).

Figure 5. Solar lanterns allow work to continue after nightfall in Uttar Pradesh, India (Source: National Geographic).

Figure 6. In Odisha, villagers use solar lamps to fish at night (Source: National Geographic).

Figure 7. Solar lamps enable Ugandan mechanics to extend their repair shop hours (Source: National Geographic).

Small-scale SHS increase energy access. A solar PV system contains solar panels that each have a specified number of solar cells based on the amount of electricity needed per panel. This application of solar technology uses the sun to power appliances or in a thermal capacity, heat water or other fluids in collectors. The water is then stored in large storage tanks in the event that the sun is not available, such as at night, thereby saving electricity that would otherwise have been employed to heat the water. SHS facilitate increased access to household appliances powered by the simple system (Figure 8) (Dahlke, 2011).

Deep research in Bangladesh as to the potential for SHS to alleviate poverty shows positive findings: first, SHS is a financially attractive solution for small medium enterprises and households with lighting and entertainment usages.

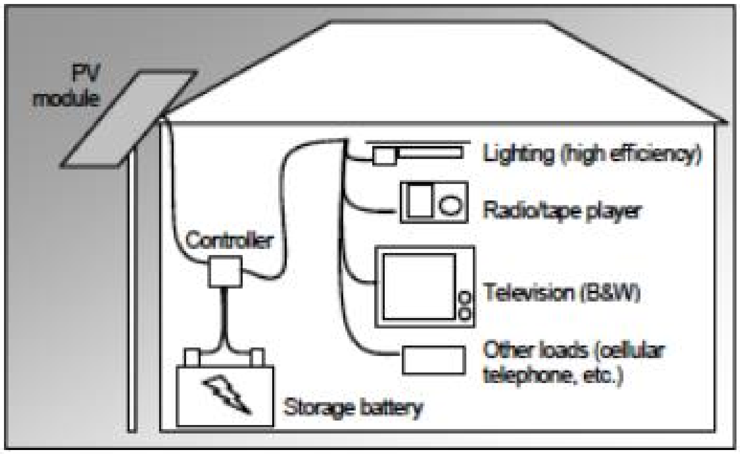

Figure 8. Solar Home System schematic shows how PV modules can power household appliances along the energy access ladder.

Households with sole lighting requirements do not mirror the same positive return on financial and economic investment without considering social benefits (Mondal, 2009). Second, "reduction of kerosene usage was the main impact of SHSs. It resulted in less pollution, higher quality light and more hours of light in the evening, as well as less work for cleaning kerosene lamps" (Mondal et al., 2011). Further corroborating the first finding, "very few income generation activities were created after acquiring SHSs in the studied villages. But the people who were engaged with business using traditional fuel, switched to solar light that added a little bit more income due to extended working hours in the evening. Women and children were found to benefit from the quality of light for household work and studying in the evening. Users became accustomed to the better quality of light and could not perceive returning back to kerosene lamps. Solar electrification also added to the overall comfort and satisfaction of the consumers" (Mondal et al., 2011). Third, "solar electrification results a number of income generating new green employments for the rural community in Bangladesh," so while it's a good fit for villages with rural businesses, it also further supports those small enterprises, and "almost in all cases this technology is indispensable for improving environmental standard and eco-efficiency of the rural community" (Chakrabaty et al., 2011).

Similar to solar lamps, SHS have seen a rise in commercialization with private sector companies identifying these rural communities as a target market. Unlike solar lamps however, the larger upfront capital cost, increased complexity in implementation and usage, as well as the ongoing need for maintenance require more analysis to ascertain whether and how SHS can best be deployed to optimize improvements along the MPI.

Mid-scale microgrids provide off-grid systems for rural communities. A microgrid is a relatively small-scale power grid roughly producing 100kW that allows customer sites, (e.g. a village) to operate independently using its own energy generation and energy storage when connection to a central utility owned grid is not yet an option. This type of microgrid system for village application is also referred to as "small remote microgrids," however for this study's purposes and in the absence of widespread naming conventions, mid-scale microgrid refers to its relative size compared to solar lamps, SHS, and central grid. Moving along the energy access ladder, "microgrids are positioned between individual home systems, which are intended to provide only lighting, cell phone charging and a small radio, and the central grid, which is designed to provide unlimited access to electricity at all times (Lawrence Berkeley National Laboratory). Microgrids can also provide increased reliability and backup power during natural disasters if implemented in a community with grid connection.

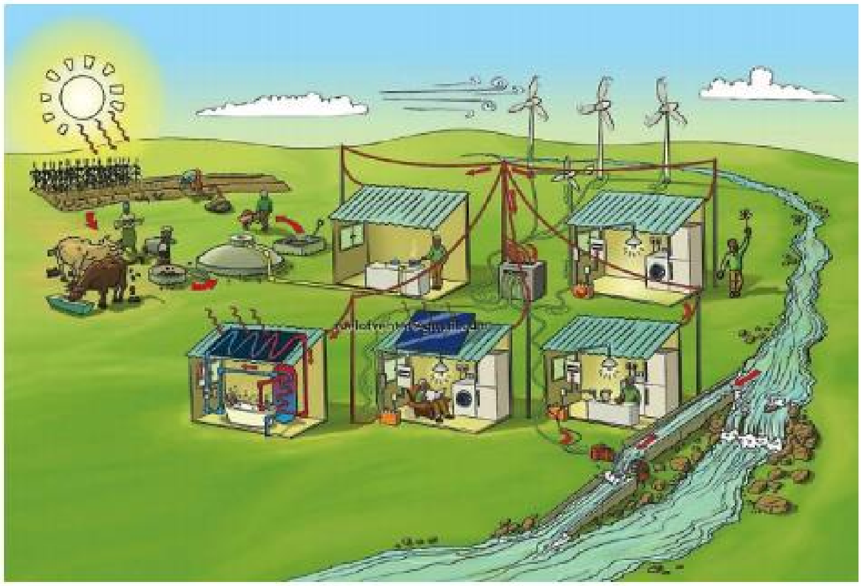

Figure 9. Schematic of solar, hydro, wind and biofuel microgrid system.

This system, as the schematic shows, often pairs renewable generation (e.g., SHS) with energy storage, such as batteries, that allow energy to be stored when there is an abundance of energy or more than can be used at the current point in time (Venter, 2012). Solar PV panels, hydro power, wind generated energy, and biofuel (from animal waste) can be captured to power pumps/appliances and/or funneled into an energy storage system (Figure 9). Stored energy can then be used during times of peak demand, i.e. periods of time when most people are using energy simultaneously like at night after the sun has set. Expanding on the solar lamp and SHS, microgrids offer more flexibility, and increased capacity to conduct more activities along the MPI categories of Education, Health and Living Standard. For example, internet connection – a service that plays a pivotal role in rural development – is often not possible without a village microgrid. The 2014 annual report of the United Nations International Telecommunications Union (ITU) states that 4.3 billion people have no access to the internet, 90% of which, to no surprise are living in developing countries (ITU, 2014). Yet the rise of mobile smartphones brings a compelling promise for connecting these large rural communities to the information and technology previously out of reach. Today, mobile phone subscriptions exceed the world's population – and mobile broadband subscriptions exceed 2.1 billion – three times higher than the number of fixed broadband connections around the world; since 2010, 82% of these worldwide net additions of new internet users come from developing countries (Dudley, 2015). By powering smartphones, microgrids enable villagers to have information at their fingertips, manage finances, and run small businesses.

Microgrid systems have seen broad implementation across countries like India, Haiti, Kenya, and Malaysia, spurred by increasing affordability of solar PV manufacturing and technological developments with battery storage. As with SHS however, microgrids necessitate more analysis to balance upfront cost, accountability of governing bodies, available management entities, and community buy-in among other factors, with the promise of rural development.

Cost and Benefit Variables for each REDS from Government and Household Perspectives

In order to account for the relative impact each REDS can have on a village's collective quality of life, cost-benefit analyses can provide a comprehensive sense of what is required to implement and what can be expected from implementation. Analyzing environmental, economic, and social considerations of these technology solutions in both per household and government standpoints offers a holistic picture of the net impact from these REDS as displayed in Tables 5 and 6.

Table 5. Holistic government cost benefit analysis of REDS and central grid connection.

GOVERNMENT COST BENEFIT ANALYSIS					
Externality	**Variable**	**Solar Lamp**	**SHS**	**Microgrid**	**Central Grid Connection**
Financial (Government)	Cost: Infrastructure development ($)	Negligible infrastructure required	Negligible infrastructure required	Negligible infrastructure required	High, power plant load analysis, grid reliability engineering, transmission lines design, subsidies
	Cost: Implementation	Negligible, often borne by developer/company	Negligible, often borne by developer/company	Negative, depending on subsidy provision	Medium, with increased utility labor
Environmental	Cost: Net GHG Emissions (tons)	Low, given avoided deforestation and use of fossil fuels	Low, given avoided deforestation and use of fossil fuels	Low, given avoided deforestation and use of fossil fuels	High, due to deforestation and fossil fuel use
Economic	Benefit: Productive/Income Generating Activity ($ against poverty line)**	Medium, with additional hours of nighttime work	Medium, with additional hours of nighttime work and small business hours	High, with additional hours of nighttime work, village services like health clinic and businesses	High, with additional hours of nighttime work, village services like health clinic and businesses
Social	Benefit: Gender Inequity (Labor Force Participation Rate)*	Mid to High, with less time dedicated to tending heat/cooking source and increased women empowerment/safety	High, with less time dedicated to tending heat/cooking source and increased women empowerment/safety	High, with less time dedicated to tending heat/cooking source and increased women empowerment, safety and entrepreneurship	High, with less time dedicated to tending heat/cooking source and increased women empowerment, safety and entrepreneurship

Table 6. Holistic per household cost benefit analysis of REDS and central grid connection.

PER HOUSEHOLD COST BENEFIT ANALYSIS					
Externality	**Variable**	**Solar Lamp**	**SHS**	**Microgrid**	**Central Grid Connection**
Financial (Household)	Cost: Installation ($/kW)	Negligible	Low, costs incurred to procure solar panels, battery, charge controller, LED lights, miscellaneous circuitry components (wiring, tools)	Medium, often subsidized, costs incurred to procure generator, operator, solar panels, battery, charge controller, LED lights, miscellaneous circuitry components (wiring, tools), demand-side mangement (meters)	Medium, often subsidized, costs incurred to build transmission lines and connect to central grid
	Cost: Purchase price ($/kWh)	Low, price range according to varying wattages	Low, clean and cheap power	Medium, often subsidized and dependent on cost of battery implemented	Medium, can leverage scale of central grid
	Cost: Operations & Maintenance ($/kWh)	Low, incurred replacement cost	Medium, incurred replacement cost, ongoing operations and maintenance	High, incurred replacement cost, ongoing operations and maintenance, tariffs and penalties	High, incurred cost of electricity
Environmental	Cost: Cleanup/Disposal ($)	Low, recyclable plastics used	Low, battery disposal an issue	Medium, based on battery disposal and generator parts	Medium, based on decommissioning and disposing of steel/pole and infrastructure
Economic	Benefit: Household Need (kW)	Medium, access to lighting	Medium, access to lighting, radio and communication	High, access to lighting, radio, communication, and entertainment	High, access to lighting, radio, communication, and entertainment
Social	Benefit: Health (kW)	Medium, with avoided indoor air pollutants	Medium, with refrigeration for nutrition and water pumps for sanitation	High, with avoided indoor air pollutants, refrigeration, water pumps, medical services and heating/cooling	High, with avoided indoor air pollutants, refrigeration, water pumps, medical services and heating/cooling
	Benefit: Education (Literacy Rates)	Medium, with increased time for reading (no longer tending a fire)	Meidum, with increased time for reading (no longer tending a fire), access to technology leveraged for learning (e.g. tablets)	High, with more increased time for reading (no longer tending a fire or fetching potable water), access to technology leveraged for learning (e.g. tablets)	High, with more increased time for reading (no longer tending a fire or fetching water), access to technology leveraged for learning (e.g. tablets)

CTRDM Variables Selection for Specific Geographies

In order to make the CTRDM tailored to specific geographies, the model's inputs need to account for a range of components that could impact feasibility and success rate of each REDS. From the number of households and proximity to grid to the economic makeup and established agencies in the community, these inputs customize the model's outputs according to a specific geography and its village's needs.

Input Requirements to Tailor REDS Selection Based on Rural Locale of Interest

Given that the range of REDS in this study places microgrids at the most complex end of the scale, the indicators of success from these systems can guide CTRDM inputs to assess the optimal fit with potential REDS. The Microgrids for Rural Electrification report published in 2014 by the United Nations Foundation and co-researched by Carnegie Mellon and UC Berkeley affiliates provides an in-depth look across seven microgrid implementation case studies to pull out best practices and nuanced lessons learned that can retrospectively guide the selection of REDS for rural communities.

Pulling from the diverse case studies, CTRDM inputs fall into five categories with specific variables in each respective component of the model:

1. Size/Profile
    a. Population Size
    b. Demand Prediction
    c. Interest
    d. Proximity to central grid
2. Environment

    a. Generation Source

3. Economic
    a. Willingness to Pay
    b. Income
    c. Economic Base
    d. Available Capital
    e. Household Energy Need
    f. Productive Ability
4. Social
    a. Responsible Management Entity
    b. Health
    c. Education
5. Governance
    a. Corruption
    b. Agency Cooperation

Size/Profile is an indicator of village energy demand. Based on the Population Size, Demand Prediction, Interest and Proximity to Central Grid, the general profile of the village can be captured. While all REDS can serve various population sizes, demand prediction, informed by surveys of existing energy services, site visits, surveys of electricity use in neighboring villages with electricity access, population growth trends and load growth in electrified areas assessment, are important aspects of this measurement (Alliance for Rural Electrification, 2011). Thus, the size of a village alone cannot dictate the optimal selection of a REDS: as the UNDP/World Bank Energy Sector Management Assistance Program (ESMAP) underscores, microgrids are neither necessary nor coveted by every community, and projected future development, in addition to the CTRDM Economic inputs like Willingness to Pay and Economic Base, can help ascertain a feasible clean tech solution.

Furthermore, analysis of microgrid installation cases from Chhattisgarh Renewable Energy Development Agency (CREDA), Orissa Renewable Energy Development Agency (OREDA) and Green Empowerment/Tonibung/PACOS (GE/T/P) show how demand can quickly outgrow a static capacity, thus making it difficult to "right-size" a system and account for future growth in demand for the life of the microgrid. "there does not seem to be an affordable, incrementally expandable microgrid that a low-income community could feasibly sustain through tariff collection," while "erratic investment over time is often difficult for donor agencies and governments" that take a "spread the wealth" approach to invest in new communities, rather than the same ones over time (Schnitzer et al., 2014). Thus, the CTRDM must capture current demand, its potential growth, and the capacity for demand-side management to understand fit with microgrid implementation.

Community Interest is difficult to profile, but is a solid marker of how viable a microgrid can be. Alternatively, while the success of solar lamps and SHS have not been predicated on expressed village interest, engagement from the community could help accelerate awareness, education, implementation and ongoing responsible usage of those solutions. To measure interest, case studies in developing countries have shown that communities can self-organize, like in Malaysia where GE/T/P, a group of non-profits and an NGO, requested a microgrid accompanied with an agreement for 10,000 hours of labor to build the project; DESI Power surveyed 100 Indian villages before selecting prime targets to install where markets could be built with demand for electricity services as an indicator of the community's investment in microgrid aimed at productive uses; Husk Power Systems (HPS) found villages in Bihar, India with diesel-fueled Build-Own-Operate-Maintain (BOOM) plants where microgrid model offered better-run, less expensive electricity; also advertised for "business anchors" in papers to identify qualified personnel that could ensure a well-run facility (Schnitzer et al., 2014).

Lastly, proximity to a central grid is an important factor to understand the probability and cost associated with connecting to a large scale grid. For example, "CREDA, an Indian government agency that designs and installs microgrids views its "solar microgrids as a stopgap solution before central grid extension, and designs its microgrids to provide lighting loads only" as opposed to the full suite of energy services this REDS typically provides (Schnitzer et al., 2014). Thus, solar lamps may have been a sufficient, less expensive, and more timely consideration in the interim, although the microgrids can now provide backup generation once connected to the central grid.

Environment takes access to generation sources into account. REDS considerations for the environment circulate around the appropriate and available generation source (UNDP Mini-Grid Design Manual, 2000). Feedstock and resource availability is a critical indicator in deciding whether there's adequate and appropriate means for fueling REDS, particularly a microgrid. Whereas solar lamps and SHS simply require solar exposure and homes in generally unshaded areas, microgrid development may alter depending on what type of renewable resources are available. From flow rates in rivers to rice husk as biofuel, the price and accessibility of these resources can be factored in to the CTRDM to help select an optimal REDS.

Economic factors are imperative to understand for REDS fit. A community's Willingness to Pay, Income, Economic Base, Available Capital, Household Energy Need, and Productive Ability comprise the Economic component of the CTRDM. Willingness to Pay is a complex variable to extrapolate, but the existence of tariffs and penalties can help indicate appetite for taking on more shared energy services. Tariffs are also important if the REDS depend on revenues for operations – as microgrids can be. While this financial mechanism "generat[es] the desired revenues to cover project cost, the tariff schedule should also contribute to making electricity more affordable (ESMAP, 2000). A "fixed monthly fee usually more suitable to the cost structure of microgrids, which consist of mostly fixed costs," so knowing the extent to which existing fixed costs are embedded in the village can also help understand Willingness to Pay (ARE, 2011). Likewise, penalties, which discourage customers from consuming more than they're permitted or making late/no payments, could indicate the current tolerance level for such financial checks and balances in the community, as well. Moreover, "most developers who were interviewed indicated that they regretted not having more sophisticated technology integrated into their installed microgrids, such as smart meters, automated payment collection technologies, or load controlling devices" but the willingness to pay from the community is requisite in order to fund these technological choices. (Schnitzer et al., 2014).

GNI per capita (Gross National Income) is a metric used to measure Income levels. Per the World Bank Atlas method, this measure provides "the sum of value added by all resident producers plus any product taxes (less subsidies) not included in the valuation of output plus net receipts of primary income (compensation of employees and property income) from abroad" (World Bank, 2014). Calculated in national currency, the GNI normalizes against the U.S. dollar and in 2014, was shown to be at $628.60 for rural communities around the world. Thus, whether the village of study is above, equal to, or above this GNI level indicates its relative ability to fund, operate, and maintain each REDS.

Income and Economic Base are related in that the makeup of rural village income is derived largely from either agrarian and/or small business activities. Matching energy services with generating income can thus create a positive feedback loop where increased energy access further boosts economic activity. In Nepal for example, a micro-hydro microgrid scheme "coupled its promotion of micro hydro dams with the agricultural processing needs of communities" (Sovacool, 2012).

Availability of Capital and funds, e.g. subsidies, grants, tariff collection, penalties, and other sources, is another indicator of REDS viability. OREDA showed that only focusing on upfront installation costs rendered successful high volumes of microgrid implementation, yet few remain operational versus the planning conducted by Chhattisgarh state government to allocate adequate subsidies to cover continuous operational, maintenance, auditing and training costs for microgrid implementation, which is transferable to other REDS experiences.

Household Energy Need and Productive Ability are related as the demands per household and income generating activities tied with increased energy access can in conjunction help indicate which REDS is most suitable for the village. For example, income generation derived from microgrid services supports a wide range of industries, from "carpentry, irrigation, telecom," even agrarian based communities that then have more stable household revenues. In turn, these communities associate a monetary value to the microgrid and find a reliable revenue source with which to supply to the microgrid operator – an important point tying back to Willingness to Pay, as microgrids often fail from customers' inability to pay tariffs, Ostrom's tragedy of the common property mentality, and "difficulty in limiting individual consumption, corruption, and conflicts" (ARE, 2011).

Maintenance & Safety costs were not built into the CTRDM, as these expenses cannot be easily standardized. Varying by generation technology, community dynamics, financial resources, local environment and types of energy services provided by the grid, maintenance needs and associated safety precautions can and should be considered separately in constructing implementation plans for REDS.

Social characteristics of a village affect REDS viability. A Responsible Management Entity is critical for social considerations of the CTRDM. Regardless of the type of entity (NGO, for-profit developer, non-profit organization, social enterprise etc.), a responsible party helps manage the inevitable increase in energy demand that comes from regular access to electricity at a consistent level. Customers become accustomed to a "powered" lifestyle and often change their usage of electricity, causing problems when resource variability (e.g. solar insolation, low-flow dry season) is present. While technical solutions like a backup diesel generator, meters for demand-side management, or planning for higher capacity can mitigate resource variability effects on microgrid generation, a strong management entity, ideally embedded within the community, is a best practice. For example, the GE/T/P Buayan microgrid tried to encourage all customers to scale down their usage during the dry season, but struggled to have customers who were used to certain appliances limit their usage to lights-only. In the context of this type of infrastructure, "people don't take care of things that they get for free," so the need for appropriate and regular tariff collection systems is clear (Martinot et al., 2002). Whether this mechanism can be in place is a critical determinant of whether microgrid performance will follow a virtuous or vicious cycle – a concept which is again transferable to other REDS (Schnitzer et al., 2014).

In addition, the importance of having community management and involvement come from within the village is reiterated for long-term projects over the twenty to twenty-five year lifetime at the risk of wasting the high upfront investment. "It must be clear that some mechanism for organizational continuity exists and that the elements are there for a long term commitment to the project…otherwise, this effort will likely be costly, time consuming, and frustrating and in the end stagnate and collapse after the outside promoter has departed the scene" (ESMAP, 2000). In fact, community ownership/community-based management has "myriad positive impacts on the community in terms of self-governance and local buy-in into the electrification system," even more so when women can be empowered to take on these management roles as an alternative to fossil fuel-related tasks that shackle them to the household (ARE, 2011). Education, a long preparation period, and technical training can bolster this long-term workforce development.

It should be noted that based on numerous case studies, external enforcement agencies fare better than internal organizations in this role: "making a tariff higher or lower does not seem to influence the likelihood of collection as much as the decision to pay a collector from outside the community and enforcing penalties reduce the frequency of non-payment (Schnitzer et al., 2014). This nuance in social enforcement points to a best practice of employing external contractors who are salaried, and run pre-payment programs and door-to door/frequent collection.

Governance is a critical component to understanding the longevity of REDS fit. The absence of Corruption and presence of Agency Cooperation are crucial to understanding the state of governance and which REDS might be best suited for the village's situation. In order to understand the level of corruption, preliminary research in the current dealings of the village should be proactively conducted. For example, HPS uncovered instances where HPS employees colluded with local rice mills to increase the rice husk prices significantly – an important reminder that developer contracts can help set expectations for reliability and lower prices with feedstock providers. In addition, DESI Power's contract with a Vodaphone cell phone tower operator also became subject to collusion; the tower operator contracted under DESI Power purchased electricity outside of Vodaphone's knowledge. As a result, the tower operator was able to turn a profit on the fuel that the diesel supplier continued to deliver to the tower.

Agency cooperation is also important to understand the ability for alignment with government bodies, as it's directly correlated with REDS sustainability. For example, if governmental plans call for central grid expansion, microgrid systems should be matched with those areas not within the grid expansion territories. Electricité d'Haiti (EDH), a national utility, ratified a provision that allows for private developers to "build, own and operate microgrids in areas not presently covered by EDH, so long as they are public-private partnerships. It further indicates that the towns being served by the microgrid operators may continue to do so upon the arrival of an interconnection with the central grid" (Schnitzer et al., 2014).

Table 7. Holistic per household cost benefit analysis of REDS and central grid connection.

Category	Input	Description	Village Profile
Size/Profile	Population Size	Number of inhabitants	Small (<5,000)
	Demand Prediction	Population growth	Rural growth ~1%
		Neighboring electricity use as proxy or load growth in electrified areas	Large (>30 kWh/month)
	Interest	Expressed interest to government or utility	Yes
	Proximity to central grid	Miles	Medium (50 - 150 km)
Environment	Generation Source	Biofuel	Yes
		Hydro	Yes
		Solar	Yes
Economic	Willingness to Pay	Existing tariffs	No
	Income	Relative to GNI $628.60	= GNI
	Economic Base	Agrarian %	Minority
		Small Business %	Majority
	Available Capital	Gov't/Utility	$ 30,000
		Local body, e.g. NGO	$ 1,500
		Utility, e.g. rebates, incentives	$ 10,000
		Developer	$ 30,000
	Household Energy Need	Lighting Radio/Music Communication Potable Water	Large (6 kWh/month)
	Productive Ability	Income generating uses to power equipment used by workers from 10 households	Medium (5 - 20 kWh/month)
Social	Responsible Management Entity	Evidence of trustworthiness/buy-in	Yes
	Health	Need for medical services in rural clinic for 100 households	Medium (0.5 - 1 kWh/month)
	Education	Need for lighting, water pumping, copying, computer, copier, TV, video, radio for 100 households	High (>1 kWh/month)
Governance	Corruption	Evidence of embezzlement, unstable government	No
	Agency Cooperation	Evidence of established and interested organization	Yes

Table 7 depicts how the analysis from the literature review paired with an understanding of best practices in implementing each of these REDS can create components that guide selection of an optimal clean energy solution. This holistic framework can thus consider a specific village demographic, in addition to environmental, economic, social, and governance factors. The Village Profile (column shown in Table 7) is customizable according to the community at hand.

Chapter III

Results

Results from the CTRDM depict its ability to customize REDS selection according to a village's specific profile and the cost/benefit analysis of each solution in the context of the community's QOL indicators. The preferred hypothesis supports small-scale REDS as the overall optimal solution for rural towns given the low-upfront investment, simpler implementation, and relatively higher rates of success. This belief is tested by running two distinct Malaysian villages through the model to pinpoint which REDS are most aligned for the respective ways of life in Kampung Dew, Perak and Kenyah, Sarawak.

CTRDM Design

Creating a framework for the inputs gleaned from best practices and past implementation of REDS facilitates the CTRDM's ability to tailor its selection of REDS to the rural locale of interest. In the model, the categories of size, environmental constraints, economic profile, social considerations, and existing governance are broken down into individual inputs, each with an explanatory description. These inputs are then assessed via relevant measurement where data is available. For example, population size is noted by the number of inhabitants – "Small (<5,000), Medium (5,000 – 10,000), and Large (10,000-50,000)" – which each correspond to a CTRDM score. Household Energy Need and Productive Ability are based on kWh monthly usage classified by "Small (2 kWh/month), Medium (4 kWh/month), and Large (6 kWh/month)" and "Small (<5 kWh/month), Medium (5 - 20 kWh/month), and Large (>20 kWh/month)" respectively. These usage cases correlate with the range of REDS, as solar lamps can generally meet the needs of simple lighting and appliance needs, while larger capacity entails SHS or microgrid solutions. In this manner, each input has a classification that awards a score to each REDS based on feasibility given the input.

Scoring is set according to the MDPI (Figure 3), typical energy service requirements for off-grid populations in developing countries (Figure 4), and straightforward facts based on specific community research (e.g. does the village have a biofuel source for energy production or does a responsible management entity exist to run an energy system).

Pairing these standards with the Cost/Benefit analysis of each REDS, the CTRDM score spans a range of -1 to 1. If -1, the REDS in this instance would bring a net cost and negative impact to the village given a holistic assessment of the financial, environmental, economic and social considerations of implementing the solution. A score of -0.5 signals that this input's measurement, could potentially be detrimental to implementation of the REDS (e.g. the absence of existing tariffs in a village suggests that microgrid management may be difficult, but does not preclude the success of installing a system and then setting up workable tariffs to sustain responsible use of energy.) On the range, 0 represents a lack of fit; for example, a solar lamp would simply not address the energy needs of a household with large usage (6 kWh/month). If it did at first, it would only exacerbate the inevitable household fuel transition and climb up the energy ladder as shown in Figure 5. So while solar lamps are not detrimental to villages with this high level of energy need, they do not offer a sustainable solution and are scored a 0 on the CTRDM scale.

In the positive end of the spectrum, a score of 0.5 signifies a potentially helpful input that is not required for maximum output. For instance, a village that has proactively self-organized and expressed interest in installing REDS to the governing body or utility, would likely be predisposed to purchasing solar lamps. However, communities that do not see this level of organization can still benefit from the additional light bought and consumed on an individual level. SHS and microgrids receive a higher score of 1, as the literature review shows how this level of interest is indicative of successful self-management of energy systems. Thus, a rating of 1 represents a net benefit, in contrast to the -1 score. For example, if the sum of available capital from a government/utility, local body, and/or private developer exceeds the hard costs of a REDS, there is a net benefit (represented by a score of 1) for that particular economic input in the CTRDM. In other words, if the available funding, rebates, incentives, and subsidies outweigh the hard costs borne by the villager for a SHS, that solution's net economic benefit is delineated by the positive score.

Thus, by drawing on standards and integrating insights from the literature review and Cost/Benefit analysis, the CTRDM can assign a score to each input. In aggregate, these scores rank REDS based on fit to the village's customized profile. A summary of the CTRDM range is shown below in Table 8:

Table 8. CTRDM input REDS rating key.

CTRDM Input REDS Rating Key	
-1	Net cost
-0.5	Potentially detrimental component
0	Not a fit
0.5	Not a necessary component, potentially helpful
1	Net benefit

This model's assumptions are further detailed in the "Inputs Key" of the CTRDM shown in Table 9 with a sample of the model shown in Table 10.

Table 9. CTRDM inputs key.

Size/Profile	Interest	Expressed interest to government or utility	Yes	No	
	Population Size	#	Small (<5,000)	Medium (5,000 - 10,000)	Large (10,000 - 50,000+)
	Demand Prediction	Population growth	Rural growth ~1%	Rural growth >1%	
		Neighboring electricity use proxy or load growth in electrified areas	Small (<3 kWh/month)	Medium (3 - 30	Large (>30 kWh/month)
	Proximity to central grid	Miles	Low (<50 km)	Medium (50 - 150 km)	High (>150 km)
Environment	Generation Source	Type	Yes	No	
Economic	Willingness to Pay	Existing tariffs	Yes	No	
	Income	Relative to GNI $628.60	< GNI	= GNI	> GNI
	Economic Base	Agrarian	Majority	Minority	
		Small Business	Majority	Minority	
	Available Capital	Gov't/Utility			
		Local body, e.g. NGO			
		Utility, e.g. rebates, incentives			
		Developer			
	Household Energy Need	Lighting	Small (2 kWh/month)	Medium (4 kWh/month)	Large (6 kWh/month)
		Radio/Music			
		Communication			
		Potable Water			
	Productive	Income generating uses to power equipment	Small (<5 kWh/month)	Medium (5 - 20 kWh/mon	Large (>20 kWh/month)
Social	Responsible Management Entity		Yes	No	
	Health	Medical services in rural clinic for 100 households	Low (0.5 kWh/month)	Medium (0.5 - 1 kWh/mo	High (>1 kWh/month)
	Education	Lighting, water pumping, copying, computer, copier, TV, video, radio for 100 households	Low (0.5 kWh/month)	Medium (0.5 - 1 kWh/mo	High (>1 kWh/month)
Governance	Corruption	Evidence of embezzlement, unstable government	Yes	No	
	Agency Cooperation	Evidence of established and interested organization	Yes	No	

Table 10. Clean Tech Rural Development Model sample.

Clean Tech Rural Development Model (CTRDM)						
Category	**Input**	**Description**	**Village Profile**	**Solar Lamp**	**SHS**	**Microgrid**
Size/Profile	Population Size	Number of inhabitants	Small (<5,000)	1.0	0.0	0.0
	Demand Prediction	Population growth	Rural growth ~1%	0.5	1.5	1.5
		Neighboring electricity use as proxy or load growth in electrified areas	Large (>30 kWh/month)	0.0	0.0	1.0
	Interest	Expressed interest to government or utility	Yes	0.5	1.0	1.5
	Proximity to central grid	Miles	Medium (50 - 150 km)	1.0	3.0	2.0
Environment	Generation Source	Biofuel	Yes	0.0	0.0	1.0
		Hydro	Yes	0.0	0.0	1.0
		Solar	Yes	1.0	1.0	1.0
Economic	Willingness to Pay	Existing tariffs	No	0.0	0.0	-0.5
	Income	Relative to GNI $628.60	= GNI	0.0	2.5	2.0
	Economic Base	Agrarian %	Minority	0.5	0.5	0.0
		Small Business %	Majority	0.5	1.0	1.0
	Available Capital	Gov't/Utility	$ 30,000	1.0	1.0	1.0
		Local body, e.g. NGO	$ 1,500			
		Utility, e.g. rebates, incentives	$ 10,000			
		Developer	$ 30,000			
	Household Energy Need	Lighting Radio/Music Communication Potable Water	Large (6 kWh/month)	0.0	1.0	2.0
	Productive Ability	Income generating uses to power equipment used by workers from 10 households	Medium (5 - 20 kWh/month)	0.0	1.0	0.0
Social	Responsible Management Entity	Evidence of trustworthiness/buy-in	Yes	0.5	0.5	1.0
	Health	Need for medical services in rural clinic for 100 households	Medium (0.5 - 1 kWh/month)	0.0	1.0	0.0
	Education	Need for lighting, water pumping, copying, computer, copier, TV, video, radio for 100 households	High (>1 kWh/month)	0.0	0.0	1.0
Governance	Corruption	Evidence of embezzlement, unstable government	No	0.0	0.5	0.5
	Agency Cooperation	Evidence of established and interested organization	Yes	0.5	0.5	1.0
TOTAL REDS ASSESSMENT				7	16	18

CTRDM Tests: Kampung Dew, Malaysia

Kampung Dew, Taiping is a rural village in Malaysia heavily reliant on its oil palm production, which has kept the community in a relatively steady economic state. Over the past five years, the village has experienced an interesting uptick of tourist activity due to its indigenous firefly population, proven to be attractive to tourists and further spurred by national recognition through events like the Malaysian Nature Society Firefly Festival. The increased volume of visitors brings opportunity for small businesses to operate – stands that sell fresh coconut water, restaurants offering local eats, and boat operators to take tourists on the river at nightfall to wonder at the fireflies. In this milieu of economic activity and ecotourism development, the question of which energy technology can support this development is a fitting test for the CTRDM.

Table 11 can be referenced with the following model analysis. Starting with the Size/Profile category, Kampung Dew classifies as a "Small (<5,000)" village with its indigenous communities spread across four mukims (sub-districts): Asam Kumbang, Jebong, Gunung, Semanggol and Selinsing each hosting about 200 – 400 villagers. This population size scores a 1 for solar lamps, but 0 for SHS and microgrid, given the limits to supporting either of those systems with too few users, accountable parties, and inability to fund the system. Given that the village population is anticipated to grow according to the standard 1% annual rate, solar lamps are rated 0.5 with the SHS and microgrid showing more promise as implementing those REDS in larger communities has seen more success.

Table 11. Kampung Dew CTRDM results.

Clean Tech Rural Development Model (CTRDM)						
Category	**Input**	**Description**	**Village Profile**	**Solar Lamp**	**SHS**	**Microgrid**
Size/Profile	Population Size	Number of inhabitants	Small (<5,000)	1.0	0.0	0.0
	Demand Prediction	Population growth	Rural growth ~1%	0.5	1.5	1.5
		Neighboring electricity use as proxy or load growth in electrified areas	Large (>30 kWh/month)	0.0	0.0	1.0
	Interest	Expressed interest to government or utility	No	0.0	0.0	0.0
	Proximity to central grid	Miles	Medium (50 - 150 km)	1.0	1.0	2.0
Environment	Generation Source	Biofuel	Yes	0.0	0.0	1.0
		Hydro	Yes	0.0	0.0	1.0
		Solar	Yes	1.0	1.0	1.0
Economic	Willingness to Pay	Existing tariffs	No	0.0	0.0	-0.5
	Income	Relative to GNI $628.60	= GNI	0.0	2.5	2.0
	Economic Base	Agrarian %	Minority	0.5	0.5	0.0
		Small Business %	Majority	0.5	1.0	1.0
	Available Capital	Gov't/Utility	$ 30,000	1.0	1.0	1.0
		Local body, e.g. NGO	$ 1,500			
		Utility, e.g. rebates, incentives	$ 10,000			
		Developer	$ 30,000			
	Household Energy Need	Lighting Radio/Music Communication Potable Water	Large (6 kWh/month)	0.0	1.0	2.0
	Productive Ability	Income generating uses to power equipment used by workers from 10 households	Medium (5 - 20 kWh/month)	0.0	1.0	0.0
Social	Responsible Management Entity	Evidence of trustworthiness/buy-in	Yes	0.5	0.5	1.0
	Health	Need for medical services in rural clinic for 100 households	Medium (0.5 - 1 kWh/month)	0.0	1.0	0.0
	Education	Need for lighting, water pumping, copying, computer, copier, TV, video, radio for 100 households	High (>1 kWh/month)	0.0	0.0	1.0
Governance	Corruption	Evidence of embezzlement, unstable government	No	0.0	0.5	0.5
	Agency Cooperation	Evidence of established and interested organization	Yes	0.5	0.5	1.0
TOTAL REDS ASSESSMENT				6.5	13	16.5

A constraint of the CTRDM is in modeling out effects over time, as steady population growth would push the scale towards optimizing with a microgrid. Given limitations to the predictive ability of this model, the scale scores REDS based on current data and accounts for future growth by assuming steady inclines at the same rate. In other words, if the rate of population growth is set at 1% per year in Kampung Dew, the model maintains that assumption going forward.

Using neighboring electricity consumption as a proxy for load growth, this community ranks “Large (>30 kWh/month)” as the towns and cities around Taiping show suburban development and steady economic activity. As the state capital, Taiping is situated on the Perak highway and houses a historic railway station built to transport ore from tin mines. With recent modernization of this station, the city will service travel to Ipoh, Padang Besar and Kuala Lumpur, connecting it and its surrounding villages to potentially more economic activity. This growth results in a high microgrid score, given the inevitable load increase from households and small businesses looking to keep up with urbanization.

Kampung Dew has not shown any signs of self-organization to express interest for energy alternatives. The absence of activity in this regard is likely due to its thriving ecotourism business that centers on nighttime boat tours in the firefly-dense mangrove swamps. Light pollution would temper the ability to see and appreciate the natural phenomenon created by these firefly colonies that routinely synchronize their flashes in displays of social interaction. Thus, the CTRDM ranks a neutral score of 0 across the board for this lack of expressed interest to date.

In addition, the village’s proximity to the central grid is deemed “Medium (50 – 150km),” ranking solar lamp/SHS and then microgrid, in order of increasing feasibility. If the mukims were farther from the grid, solar lamps are more attractive in terms of lighting up the villages without incurring the hefty cost of transmission line infrastructure; similarly, SHS would provide a power source off-grid, but require more start-up costs to establish. Microgrids are likely the most helpful, not in the sense of offering backup power, but creating island utilities for each village. As the community grows and urbanization potentially brings the grid closer to town, the value of a microgrid in providing power reliability also increases. Based solely on the village Size/Profile category, microgrid shows the greatest match on the CTRDM scale.

The Environment category takes a straightforward stock of generation sources – for Kampung Dew, its fishing village river access and geographical location provide the possibility of both hydro and solar. Although relatively recent, the use of palm oil as biofuel provides the opportunity to turn a major export from its plantations into a sustainable energy source. As a result, microgrids are again the highest rank amongst REDS, as solar provides a score of 1 for both solar lamp and SHS, but the availability of hydro power, only gives a positive ranking to microgrid.

In contrast, the assessed Economic inputs point to SHS as the most fitting REDS for a number of factors. First, the lack of existing tariffs is a potential red flag for successful microgrid implementation, while neutral for solar technology as multiple solar lamp and SHS case studies show positive outcomes without any mandated tariffs. Second, Kampung Dew income levels are less than GNI, indicating that the villagers' ability to fund, operate, and maintain SHS is better matched than financing a microgrid; it does not preclude solar lamps from bringing positive benefits. Third, the village's economic base is made up in large part of agrarian activity with a minority percentage of small businesses – boating tours, grocers, and convenience stores that cater to the budding tourist population; this dynamic favors solar solutions that require less upfront capital and discourages investing in microgrid development until the economic base of small businesses is large enough to warrant the demand for excess power generation. Fourth, the available capital is neutral to all REDS, as the combination of government, local NGO, utility rebates, and developer capital are in aggregate greater than the costs needed to implement each of the REDS as discovered through the cost/benefit analysis. For example, Tenaga Nasional Berhad's (TNB) transmission division, Grid Nasional, connects consumers along the span of Peninsular Malaysia to independent power producers and electricity generation stations. Part of TNB's offerings through the statutory agency, Sustainable Energy Development Authority (SEDA), include a program promoting solar installation and production. This program established a Feed-In-Tariff that facilitates the sale of renewable energy back to the utility at a fixed premium rate per kilowatt hour of electricity generated over a specific period of time. For a system under 4 kW, RM 1.3708 can be expected in payment per unit of electricity produced, guaranteed over 21 years. In sum, RM 7,000 would be feasible annually with a range of revenue potential according to the size of the solar PV system (Lau, 2016). Homes in Kampung Dew with larger SHS or microgrid systems could thus sell clean back power to TNB and recover implementation costs over a reasonable payback period.

Lastly, the respective "Large (6 kWh/month" Household Energy Need inputs point to SHS and microgrid solutions as equally good fits based on consumer demand for lighting, entertainment and communication appliances, and potable water needs. However, the "Medium (5 – 20 kWh/month)" input for Productive ability suggests that the larger capacity and associated cost of a microgrid system may not be as effective as SHS for this village. Together, the Economic inputs indicate that the best REDS for Kampung Dew would be SHS.

The Social assessment nevertheless, points back to microgrid alignment, as does the Governance category. Kampung Dew has not demonstrated that it has responsible management entities that could run SHS or microgrids; as evident by the boat operators who at times disturb firefly colonies with their flashing lights during night tours, the community's is putting its very income source at risk through irresponsible practices.   Where the microgrid scores well is with the stable local government and ties to the state, given recent recognition for its budding ecotourism.

In conclusion, pulling in specific inputs according to Kampung Dew's demographic and current economic make-up, the CTRDM points to a microgrid solution to spur appropriate development in a sustainable fashion for this village. Table 11 portrays the model specifications for this village.

CTRDM Tests: Kenyah, Malaysia

Across the sea from Peninsular Malaysia, a small rural village named Kenyah, is home to one of 27 remaining communities of the Orang Ulu. This ethnic designation refers to "remote people" or "people of the interior" with populations ranging from less than 300 to 25,000 in the various villages spread across the highlands and middle/upper reaches of Sarawak. Kenyah homes are distinct, as extended families build and inhabit longhouses on elevated land near the river bank. Proximity to water lends itself to rice paddies and other cash crop cultivation, like rubber, pepper and cocoa, given the suitable tropical weather.

With abundant access to rich natural resources, the Orang Ulu way of life has been threatened by large-scale economic development in the form of timber logging and hydro-electric dams. 75% of the Sarawak state is covered by tropical forest, which has led to the well-known tragedy of deforestation in the name of state revenues and at the expense of indigenous populations. Self-organized opposition from Orang Ulu communities, including Kenyah, began as early as in March 1987, when the Punan people built blockades across critical road and river systems to prevent further felling of trees. Rather than address the group's grievances, arrests were made and Draconian legislation established that any interference with logging would be considered a criminal offense. While international groups, like the European Union have shown support in the way of a worldwide suspension on tropical hardwood imports, logging has persisted.

The Pontianak River and its tributaries have also attracted hydro-electric dam developers to Sarawak. As a result of these projects, nomadic villagers have been displaced and forced to shift to settled farming; unsustainable employment limited only to the time period of dam construction has left many jobless, and devastating floods remain a risk.

With this social, economic, and political make-up of indigenous people, clean technology is not an obvious solution to combat the pressures from large-scale development. Running the Kenyah demographics through the CTRDM, however, yields interesting results by assessing solutions within the context of the quality of life the Orang Ulu people would like to maintain.

Table 12. Kenyah CTRDM results.

Clean Tech Rural Development Model (CTRDM)						
Category	**Input**	**Description**	**Village Profile**	**Solar Lamp**	**SHS**	**Microgrid**
Size/Profile	Population Size	Number of inhabitants	Medium (5,000 - 10,000)	-1.0	1.0	0.0
	Demand Prediction	Population growth	Rural growth ~1%	0.5	1.5	1.5
		Neighboring electricity use as proxy or load growth in electrified areas	Small (<3 kWh/month)	1.0	0.0	0.0
	Interest	Expressed interest to government or utility	No	0.0	0.0	0.0
	Proximity to central grid	Miles	High (>150 km)	1.0	2.0	2.0
Environment	Generation Source	Biofuel	Yes	0.0	0.0	1.0
		Hydro	Yes	0.0	0.0	1.0
		Solar	Yes	1.0	1.0	1.0
Economic	Willingness to Pay	Existing tariffs	No	0.0	0.0	-0.5
	Income	Relative to GNI $628.60	< GNI	0.5	2.0	1.0
	Economic Base	Agrarian %	Majority	1.0	1.0	1.0
		Small Business %	Minority	0.0	0.5	-0.5
	Available Capital	Gov't/Utility	$ 30,000	1.0	1.0	1.0
		Local body, e.g. NGO	$ -			
		Utility, e.g. rebates, incentives	$ -			
		Developer	$ 15,000			
	Household Energy Need	Lighting Radio/Music Communication Potable Water	Small (2 kWh/month)	0.5	0.0	0.0
	Productive Ability	Income generating uses to power equipment used by workers from 10 households	Small (<5 kWh/month)	1.0	0.0	0.0
Social	Responsible Management Entity	Evidence of trustworthiness/buy-in	Yes	0.5	0.5	1.0
	Health	Need for medical services in rural clinic for 100 households	Low (0.5 kWh/month)	0.5	0.0	0.0
	Education	Need for lighting, water pumping, copying, computer, copier, TV, video, radio for 100 households	Low (0.5 kWh/month)	0.5	0.0	0.0
Governance	Corruption	Evidence of embezzlement, unstable government	No	0.0	0.5	0.5
	Agency Cooperation	Evidence of established and interested organization	No	0.0	0.0	-0.5
TOTAL REDS ASSESSMENT				8	11	9.5

Table 12 can be used to reference the following analysis of REDS assessment for this village. Kenyah's Size/Profile points to either solar lamps or SHS as solid technological fits to match the roughly 7,500 population, expected growth rate below the average 1%, and minimal electricity needs given the dominant farming way of life. Microgrid solutions would offer unnecessarily large capacities to subsist power needs of families looking largely for lighting and water conveyance solutions. In contrast, the village's ideal proximity to hydro power, biofuel stock, and solar generation rank microgrids as the optimal REDS.

An Economic review identifies SHS as the best REDS for Kenyah, then solar lamps, followed by microgrids. With an agrarian-based economy and in the absence of small businesses, relatively low GNI is characteristic. Orang Ulu live off the land, and rely on its health for sustenance and shelter. Thus, household energy needs and productive ability to generate income from electricity is small, mainly facilitating lighting, cooking, and irrigation. SHS would enhance the longhouses of Kenyah villagers, where shared solar generated power could facilitate night time activities like wood carving, tool repair, and literacy. The natural organization around these longhouses creates economies of scale for system implementation and ongoing maintenance around fewer households.

Similarly, a Social assessment points to SHS as the optimal REDS. The ability to self-organize is evident through the activist efforts against logging and deforestation. This capacity to mobilize the community implies an ability to rally the village around adoption of a new technology, maintain the system, and manage equitable use of/payment for energy production. The smaller population size and organization around the longhouses indicates a medium production need for health services (0.5 – 1 kWh/month for 100 households), while even lower for education (0.5 kWh/month). This level of demand skews the social rating towards an SHS that can handle this capacity without incurring the greater costs of a microgrid system, yet offer more flexibility than solar lamps limited lighting usage.

Analysis of the Governance mechanisms in place show favorability for SHS to be successfully deployed. Given the agrarian focus, Kenyah has not experienced embezzlement or unstable community rule. In the absence of corruption, SHS and microgrids are feasible, while solar lamps are generally able to be adopted regardless of the stability of governing bodies. However, where SHS and microgrid differ is with the establishment of an interested organization. Without express commitment or previous awareness around sources of clean energy, the microgrid score receives a potentially detrimental rank (-0.5), whereas this absence is less critical for solar lamps and SHS REDS that can be implemented in shorter ramp up time and continue to provide benefits to its users despite no prior demand for them.

In conclusion, in contrast to Kampung Dew's analysis resulting in a microgrid REDS, the more rural and agrarian based Kenyah could see gains from installing SHS in its longhouse homes. While it may not directly help combat the effects of deforestation, the ability to irrigate its farmlands, especially as villagers are displaced at the whim of hydrodam construction allows for their continued way of life. In addition, lighting from SHS could alleviate their own reliance on wood fuels for fire, while improving indoor air quality through cleaner means of cooking indoors. Perhaps most importantly, the CTRDM dissects each layer of Kenyah's social, economic, and political community construct to select an optimal REDS that will maintain and potentially enhance the lifestyles of the Orang Ulu – an outcome not possible without analysis of these individual components.

Chapter IV

Discussion

This research provides several important findings in today's world of rural development:

- Dissects the ability of small scale solar technologies (vs. large scale electrification) to serve as sustainable development solutions that address implications of energy poverty in rural areas
- Depicts how a holistic cost/benefit analysis can inform the Quality of Life outcomes to be expected from clean technology solutions that are implemented
- Develops a customizable model that indicates which REDS is most optimal for a specific community, as evident from two distinct case studies (Kampung Dew, Taiping and Kenyah, Sarawak)

A holistic methodology that accounts for environmental, economic, social, and governance factors specific to a village is necessary to fully capture the cost/benefit of implementing REDS and the potential to do so in a thoughtful way. The Clean Tech Rural Development Model offers a systematic means for assessing these components and selecting a REDS that would have the highest net benefit, greatest chance of sustainable success, and best match against a community's quality of life. Clean tech investment can thus be funneled to the most optimal REDS for a select community, and deficiencies in regulations can be proactively addressed to improve the longevity of clean tech programs.

Small-scale REDS like solar lamps are attractive for their ability to scale and low upfront cost, and as a result, often receive the most attention and investment from large corporations looking for simple ways to bring power to rural communities. However, this whole-systems approach embedded in the CTRDM provides a more considerate way of identifying REDS for longer-term and more sustainable impact. As evident from the case studies on two different rural communities – Kampung Dew and Kenyah – solar lamps were not appropriate REDS for either. While they would bring light and the ability to extend work hours of the small businesses catered to tourists in Kampung Dew, and undoubtedly extend productive time for farmers in Kenyah, both of those communities can find more lasting benefits in other REDS. The hypothesis favoring small-scale REDS as the overall optimal solution for rural towns is thus disproved in running two distinct Malaysian villages through the model and finding that a microgrid and SHS were most aligned for Kampung Dew in Perak and Kenyah in Sarawak respectively.

Significance for Public Entities

Groups like the Asian Development Bank and United Nations Development Program can shift funding from large-scale infrastructure projects that have generally failed (e.g. electrification, hydro-electric dams) and instead, take guidance from the CTRDM. This model will improve the return on their development dollars and fund specific technologies that will not only yield sustainable results, but also promote advancements in QOL that are aligned with MDPI.

Significance for the Clean Tech Private Sector

Venture capital firms can funnel their investment to more targeted development solutions, while large enterprises looking to make an impact can likewise support projects that are more attuned to the types of development that closely align with QOL goals of a community. For example, rather than having Panasonic arbitrarily target the dissemination of 100,000 solar lanterns, its funding could be aimed at specific REDS through a CTRDM assessment.

Recommendations for Further Research

This study provides critical insight into the ability of clean technology to spur meaningful and sustainable rural development, while also offering a platform on which to build deeper understanding through additional fields of research.

First, as technology advances, the cost-benefit model can be refined with the latest financial data, e.g. costs associated with manufacturing, implementing, and maintaining REDS. To keep the model relevant, costs for solar panels, batteries, inverters, LED lamps, and other components should be reflected in the CTRDM, as they will likely continue to decline, thereby impacting the holistic assessment of each solution.

Second, using this replicable methodology, less developed REDS, like leaf technology, can be incorporated into CTRDM to test the viability of new solutions to spur rural development. The CTRDM can guide pilot sites to implement REDS, increasing the likelihood that the REDS will be implemented successfully to yield high long-term impact matched to the QOL aspirations of the community.

Third, additional large-scale infrastructure, like hydroelectric dams, could be added to the spectrum of REDS to offer another base case against which small-scale solutions can spur development. For example, Kenyah villagers face displacement, risk of floods, and intermittent employment as a result of hydroelectric dam development. By adding the cost/benefit of this infrastructure to the CTRDM, a strong business case can be built to show how the same if not better rural development can be achieved through small-scale solutions in the CTRDM.

Conclusions

While large-scale infrastructure projects that bring power to rural villages offered the promise of economic activity, educational advancement, and healthcare improvements, electrification has largely failed to tackle long-standing issues of poverty. In addition, sources of funds and widespread support for on-grid electrification programs have diminished since the 1980s, as the aspirations driving these large-scale projects were largely not realized (Brossman, 2013).

In contrast, small-scale clean technology has seen success in fueling social progress and offers high potential to spur critical "step change" progress. For countries that have experienced rapid urban development amidst rural communities, energy access could transform quality of life in a sustainable and thoughtful manner. A customized approach to rural development through the CTRDM unlocks the power of the most optimal clean technology solution for a community to improve quality of life – and on a grander scale – revolutionizes how we approach sustainable development of rural/urban dichotomized countries.

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